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Subject: FW: Parcel C Internal Draft Phase I I-RACR for Review
Attachments: TEXT Internal Draft RACR Parcel C_04132020_ps.docx

Carl,

FYSA – You’ve drawn my attention to our site close-out/RACR documentation, and I agree with your comments. I’ve sent the team additional guidance, but think I need to have a site-closeout/RACR discussion with the HPNS team/contractors.

V/r,
Paul

From: Stoick, Paul T CIV USN (USA)
Sent: Friday, May 1, 2020 4:41 PM
To: Ohannessian, Sharon A CIV NAVFAC HQ <sharon.ohannessian@navy.mil>
Cc: Robinson, Derek J CIV USN NAVFAC SW SAN CA (USA) <derek.j.robinson1@navy.mil>
Subject: RE: Parcel C Internal Draft Phase I I-RACR for Review

Sharon,

Attached my comments on the I-RACR. Have you received Carl’s comments yet? My overarching trend on the comments is that the RACR doesn’t follow the standard RACR outline, and because of that I think is missing some key components to demonstrating Response in Place. I didn’t elaborate assuming Carl would catch this – so curious what his comments look like.

It also seems to be more project centric and includes quite a bit of CSM/pre-RA characterization background – which is fine for the overview, but the RACRs primary objective should be demonstrating the Site RAOs are or in this case for the I-RACR will be met. I think this is a product of the contractor’s in-depth focus on characterizing the CSM vs. site closeout. There should also be a clear ongoing activities section for the I-RACR to clearly have a CERCLA based exit strategy for the site/Final RACR.

Understand that’s not an easy fix – so let me know if that makes sense.

Thanks and have a great weekend!

V/r,
Paul

From: Ohannessian, Sharon A CIV NAVFAC HQ <sharon.ohannessian@navy.mil>
Sent: Wednesday, April 15, 2020 10:26 AM
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CA (USA) <derek.j.robinson1@navy.mil>

Subject: Parcel C Internal Draft Phase I I-RACR for Review

Hi Paul and Derek,

Attached is the Word file of the Parcel C Phase I internal draft I-RACR text for review. I will also upload the following files to DoD SAFE for you to download if desired to facilitate your review:

01 Internal Draft IRACR Parcel C_Tbls_Figs_Attch1.pdf

02 Appendix B through L Combined

03 Appendix M

04 Appendix N

05 Appendix A

Appendix A is a duplicate of the previous RAWPA and the file is large – it also has a 1 Gigabyte laboratory report which [was NOT uploaded to DoD SAFE](#).

Comments are due to me before May 1, as the draft is due to the BCT on May 14.

Thank you!

Sharon



**Naval Facilities Engineering Command Southwest BRAC
PMO West
San Diego, CA**

**INTERNAL DRAFT
INTERIM REMEDIAL ACTION COMPLETION REPORT
PARCEL C, REMEDIAL UNITS C1, C2, C4, AND C5**

Hunters Point Naval Shipyard, San Francisco, California

April 2020

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CA 92147.**

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**INTERNAL DRAFT
INTERIM REMEDIAL ACTION COMPLETION REPORT
PARCEL C, REMEDIAL UNITS C1, C2, C4, AND C5**

Hunters Point Naval Shipyard, San Francisco, California

April 2020

Prepared for:

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ACRONYMS AND ABBREVIATIONS

%	percent
µg/L	micrograms per liter
2-D	two-dimensional
3-D	three-dimensional
ACM	aerobic co-metabolism
ADM	aerobic direct metabolism
Alliance	Alliance Compliance Group Joint Venture
amsl	above mean sea level
ANCM	anaerobic co-metabolically
ANDM	anaerobic direct metabolism
ASTM	American Society for Testing and Materials
ATC	active treatment criteria
BGMP	Basewide Groundwater Monitoring Program
bgs	below ground surface
BCT	BRAC Cleanup Team
BMP	best management practices
BRAC	Base Realignment and Closure
CB	chlorobenzene
CDM Smith	CDM Federal Programs Corporation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFC	chlorofluorocarbon
cm/s	centimeters per second
COC	chemical of concern
CQC	construction quality control
CSM	conceptual site model
CSO	Caretaker Site Officer
CT	carbon tetrachloride
DCB	dichlorobenzene
DCE	dichloroethene
DCM	dichloromethane
<i>Dhc</i>	<i>Dehalococcoides</i>
DNA	deoxyribonucleic acid
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	United States Department of Defense
DQO	data quality objective
DTSC	California Department of Toxic Substances Control
ECC-Insight	Environmental Chemical Corporation - Insight Environmental, Engineering and Construction Inc.
EPA	United States Environmental Protection Agency
EPP	Environmental Protection Plan

ACRONYMS AND ABBREVIATIONS

EWI	Environmental Work Instruction
F-WBZ	fractured water-bearing zone
FS	Feasibility Study
GPRS	Ground Penetrating Radar Systems LLC
HPNS	Hunters Point Naval Shipyard
IC	institutional control
IDW	investigation-derived waste
I-RACR	Interim Remedial Action Completion Report
ISB	in situ bioremediation
Kf	Franciscan Complex Bedrock
Kf-c	Franciscan Complex Bedrock - chert
Kf-CL	Lean Clay
Kf-s	Franciscan Complex Bedrock – sandstone and shale
Kf-sp	Franciscan Complex Bedrock – weathered serpentinite
LCSs	Laboratory control samples
LDC	Laboratory Data Consultants
LOD	level of detection
LNAPL	light non-aqueous phase liquid
MEK	methyl ethyl ketone
mg/L	milligram per liter
MNA	monitored natural attenuation
mph	miles per hour
MS/MSD	Matrix spike/matrix spike duplicates
NAVFAC SW	Naval Facilities Engineering Command Southwest
Navy	United States Department of the Navy
NFG	National Functional Guidelines
NPL	National Priorities List
ORP	oxidation-reduction potential
PAH	polyaromatic hydrocarbon
PARCCS	precision, accuracy, representativeness, completeness, and comparability, completeness, and sensitivity
PCB	polychlorinated biphenyl
PCE	tetrachloroethene
PMO	Project Management Office
PQL	Practical quantitation limit
PPE	personal protective equipment
pre-RA	preliminary remedial action
PUC	Public Utilities Commission
PVC	polyvinyl chloride
QA	Quality Assurance
Qaf	Artificial Fill

ACRONYMS AND ABBREVIATIONS

Qbm	Bay Mud
QC	quality control
qPCR	quantitative polymerase chain reaction
Qtf	Tidal Flat Deposit
Qu	Undifferentiated Sediments
Quus	Undifferentiated Upper Sands
RA	remedial action
RAO	remedial action objective
RAMP	Remedial Action Monitoring Plan
RAWP	Remedial Action Work Plan
RAWPA	Remedial Action Work Plan Addendum
RD	reductive dechlorination
RDDBR	Remedial Design and Design Basis Report
RG	remediation goal
ROD	record of decision
ROICC	Resident Officer in Charge of Construction
RPM	Remedial Project Manager
RU	remedial unit
SAP	Sampling and Analysis Plan
SFRA	San Francisco Redevelopment Agency
sonic	rotosonic
SOP	standard operating procedure
SVOC	semivolatile organic compound
TCE	trichloroethene
TOC	total organic carbon
TPH	total petroleum hydrocarbons
USCS	Unified Soil Classification System
VFA	volatile fatty acid
VC	vinyl chloride
VOC	volatile organic compound
Water Board	California Regional Water Quality Control Board
WMP	Waste Management Plan
wt%	percent by weight
ZVI	zero-valent iron

EXECUTIVE SUMMARY

This Interim-Remedial Action Completion Report (I-RACR) describes the implementation and the results of remedial action (RA) conducted at Remedial Units (RU)-C1 and RU-C2 located in Parcel C at Hunters Point Naval Shipyard (HPNS), San Francisco, California (**Figure 1-1**) between November 2017 and December 2019 in accordance with the Remedial Action Work Plan (RAWP; ECC-Insight and CDM Smith 2017) and Remedial Action Work Plan Addendum (RAWPA; ECC-Insight and CDM Smith 2019a). The RA was conducted under the CERCLA (Comprehensive Environmental Response, Compensation and Liability Act of 1980) to achieve remedial action objectives (RAOs) identified in the Final Record of Decision (ROD) for Parcel C (U.S. Department of the Navy [Navy], 2010). The Final ROD selected a remedy for soil which included excavation with offsite disposal, soil vapor extraction (SVE), installation of a durable cover, and implementation of institutional controls. The selected remedy in the Final ROD for groundwater included active treatment using zero-valent iron (ZVI), and in situ bioremediation (ISB), followed by monitored natural attenuation (MNA) and implementation of institutional controls.

This I-RACR presents RA activities and performance monitoring to address non-radiological contamination at RU-C1, Building 253 and RU-C2, Building 251. Soil and groundwater pre-RA characterization activities at RU-C1 and RU-C2 were conducted between November 2017 and December 2018 to fill data gaps and update the conceptual site model (CSM) to support delineation of treatment volumes for RA, as part of the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**). The results of the pre-RA characterization were input into a three-dimensional (3-D) visualization software (Leapfrog Works®) to evaluate distribution of chemicals of concern (COCs) in soil and groundwater, and refine the lateral and vertical target treatment zones.

The pre-RA characterization results were included in the RAWPA previously reviewed by the BRAC Cleanup Team (BCT) and is presented as **Appendix A** to this I-RACR. The RAWPA (**Appendix A**) documents the characterization and updated CSM in the following locations (**Figure 1-2**):

- RU-C1: RU-C1-1 and RU-C1-3/Building 253 soil and groundwater characterization
- RU-C2: Building 251, Excavation 20B-1, RU-C2-1 B-aquifer soil and groundwater characterization; RU-C2-3 soil and groundwater characterization

As documented in the RAWPA (**Appendix A**), RA for RU-C2 soil Excavation 20B-1 and the RU-C1-3 A-aquifer groundwater plume will be conducted in future RAs and reported in future groundwater RACR(s). In addition, groundwater RA is not proposed for the RU-C2-1 B-aquifer plume, consistent with RAOs established in the Parcel C ROD. As a result of the soil and groundwater characterization activities presented in the RAWPA, in situ ZVI and ISB groundwater injections, and performance monitoring were conducted in the following areas between April and December 2019 that exceeded the active treatment criteria (ATC) for groundwater at Parcel C in the A-aquifer:

- RU-C1-1 groundwater plume, where one boring RUC11HPT04, exceeded the ATC for tetrachloroethene (PCE) at 87 micrograms per liter (µg/L) (**Figure 2-1**).
- RU-C2-3 groundwater plume, where additional characterization and monitoring wells identified a hot spot for trichloroethene (TCE) at 7,800 µg/L at new performance monitoring well IR28MW941F, as part of a comingled plume with carbon tetrachloride (CT), with the highest concentration of CT reported at RUC23SB08 at 140 µg/L (**Figure 2-4**).

RU-C1-1 groundwater plume treatment. Groundwater treatment at RU-C1-1 included advancing 3 hydraulic fracturing boreholes and delivering amendment containing 6,871 pounds of ZVI and 45 gallons of emulsified vegetable oil (LactOil®) and sodium lactate (WilclearPlus®) at the target treatment zone of 7 to 15 feet below ground surface (bgs). Hydraulic fracturing in RU-C1-1 delivered amendments to promote abiotic and biotic reductive dechlorination (RD) of PCE and its lesser chlorinated degradation products within an area that exceeded ATC at boring RUC11HPT04. Performance monitoring wells were monitored before and 1-, 3-, and 6- months after the RA injections. Groundwater RA activities were successfully conducted per the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**) and amendment distribution was successful within the treatment area (**Figure 4-3**).

RU-C2-3 groundwater plume treatment. Groundwater treatment at RU-C2-3 included advancing 43 hydraulic fracturing boreholes and delivering amendment containing 242,249 pounds of ZVI and 1,088 gallons of emulsified vegetable oil (LactOil®) and sodium lactate (WilclearPlus®) at the target treatment zone of 12 to 29 feet bgs. Performance monitoring wells within and on the RU-C2-3 boundary were monitored before and 1-, 3-, and 6- months after the RA injections. Hydraulic fracturing in RU-C2-3 delivered amendments to promote abiotic and biotic RD of TCE and CT and their lesser chlorinated degradation products within an area that exceeded ATC (**Figure 4-6**). Amendment distribution was successful within the treatment volume as indicated by visual observations, tiltmetering data, iron and TOC levels, and other geochemistry changes during the post-RA monitoring period. Because hydraulic fracturing was performed in weathered bedrock for this plume, the fracture fluid is expected to propagate through the emplaced fracture network (**Figures 4-6 through 4-8**). The amendment dissolution and advective transport within the aquifer further expands the treatment volume over time beyond the original fracture network presented in **Figures 4-6 and 4-7**. Within the hotspot area near IR28MW941F, a two order of magnitude decrease in TCE concentrations were observed with substantial increases in degradation byproducts including the innocuous ethene and ethane. TCE concentrations were just above the ATC and are expected to continue to decline. Likewise, cis-1,2-dichloroethene, vinyl chloride, and CT are above ATC, but declining COC trends are expected to continue. Collectively, decreasing COC trends, increasing COC daughter product trends, high levels of *Dehalococcoides* (*Dhc*) and reductase/functional genes, and highly reducing geochemical conditions indicate that the RA was successful in promoting the removal of COC mass from RU-C2-3 via abiotic and biotic degradation mechanisms (**Table 4-5, Figure 4-10**).

Remedy in place has been achieved at plumes RU-C1-1 and RU-C2-3 with substantial reductions in COCs achieved. Continued post-RA monitoring will be conducted by the Basewide Groundwater Monitoring Program per the Parcel C Remedial Action Monitoring Plan (Indus 2020a) with results included in future Parcel C Remedial Action Monitoring Reports (e.g. IGI 2020b). Continued evaluations of groundwater trends post-RA are recommended as follows:

- Conduct 9-month and 12-month post-RA sampling and then semiannual BGMP sampling of RU-C1-1 monitoring wells IR28MW938A and IR28MW338A
- Conduct 9-month and 12-month post-RA sampling and then semiannual BGMP sampling of RUC2-3 monitoring wells IR28MW190F, IR28MW300F, IR28MW939F, IR28MW940F, and IR28MW941F

The recommended suite of analyses includes:

- Purge parameters (DO, ORP, pH, conductivity)
- Anions (full suite EPA Method 300.0)
- TOC (EPA Method 9060)

- Total Metals (EPA Method 6010B/7470A)
- Hexavalent Chromium (RU-C2-3 only, EPA Method 7199)
- VOCs (EPA Method 8260B)
- Methane/ethane/ethene/acetylene (RSK-175)
- *Dhc* spp. *vcrA*, *bvcA*, *tceA* (qPCR, lab-specific method)
- Water levels to continue to evaluate seasonal gradient shifts in RU-C2-3

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1.0 INTRODUCTION

This Interim Remedial Action Completion Report (I-RACR), was prepared by Environmental Chemical Corporation - Insight Environmental, Engineering and Construction Inc. (ECC-Insight) in association with CDM Federal Programs Corporation (CDM Smith) and summarizes the characterization and remedial actions (RAs) conducted per the Remedial Action Work Plan (RAWP) (ECC-Insight and CDM Smith 2017) and Remedial Action Work Plan Addendum (RAWPA; ECC-Insight and CDM Smith 2019a; **Appendix A**) for soil and groundwater at remedial units (RUs) RU-C1, RU-C2, RU-C4, and RU-C5 in Parcel C, located at Hunters Point Naval Shipyard (HPNS), San Francisco, California (**Figure 1-1**). This I-RACR has been prepared for the Base Realignment and Closure (BRAC) Program Management Office (PMO) West, United States Department of the Navy (Navy), Naval Facilities Engineering Command Southwest (NAVFAC SW) under Contract No. N62473-12-D-2004, Delivery Order 0013.

1.1 Project Objectives

Multiple investigations and RAs have been completed at HPNS Parcel C (**Table 1-1**). The objective of the I-RACR is to summarize the results of the following activities conducted at Parcel C between November 2017 and December 2019 per the RAWP and RAWPA (ECC-Insight and CDM Smith 2017, 2019a):

1. Soil and groundwater characterization activities at RU-C1 and RU-C2 were conducted between November 2017 and December 2018 with an updated conceptual site model (CSM), as part of the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**). The RAWPA has been previously reviewed by the BRAC Cleanup Team (BCT) and is presented as **Appendix A** to this I-RACR. The RAWPA (**Appendix A**) documents the characterization and updated CSM in the following locations (**Figure 1-2**):
 - RU-C1: RU-C1-1 and RU-C1-3/Building 253 soil and groundwater characterization
 - RU-C2: Building 251, Excavation 20B-1, RU-C2-1 B-aquifer soil and groundwater characterization; RU-C2-3 soil and groundwater characterization
2. As a result of the soil and groundwater characterization activities presented in the RAWPA (**Appendix A**), in situ zero-valent iron (ZVI) groundwater injections, baseline, and performance monitoring were conducted in the following areas between April and December 2019 and presented in this I-RACR for the following Parcel C areas:
 - RU-C1-1 groundwater plume
 - RU-C2-3 groundwater plume

The results of the in situ ZVI groundwater injections at RU-C1-1 and RU-C2-3 were input into a three-dimensional (3-D) visualization software (Leapfrog Works®) to prepare an updated CSM.

The proposed characterization and RAs were conducted under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 to achieve remedial action objectives (RAOs) per the Final Record of Decision (ROD) for Parcel C (Navy 2010) and the Final Remedial Design and Design Basis Report (RDDBR) (Kleinfelder and CH2MHILL joint venture [KCH] 2012).

The RAs addressed in this I-RACR have not been identified as radiologically impacted. Characterization activities were conducted in Buildings 253 and 211 where a radiological containment area was established and are documented as part of the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**).

1.2 Regulatory Framework and Remedial Action Objectives for Parcel C

This RA is administered in accordance with CERCLA (1980) as amended by the Superfund Amendments and Reauthorization Act of 1986 and the National Oil and Hazardous Substances Pollution Contingency Plan. Regulatory agencies overseeing this work include the United States Environmental Protection Agency (EPA), California Department of Toxic Substances Control (DTSC), and California Regional Water Quality Control Board (Water Board). The Navy, EPA, DTSC, and the Water Board, along with the City and County of San Francisco are collectively referred to as the BCT. A summary of the Parcel C RAs previously conducted is provided in **Table 1-1**. The remediation goals (RGs) for soil and groundwater are identified in Tables 3 and 4 of the ROD and replicated in this I-RACR as **Attachment 1**.

As defined in the ROD (Navy 2010), Parcel C nonradiological soil and groundwater RAOs are as follows:

Soil RAOs:

1. Prevent or minimize exposure to organic and inorganic chemicals in soil at concentrations above RGs developed in the human health risk assessment for the following exposure pathways:
 - a) Ingestion of, outdoor inhalation of, and dermal exposure to surface and subsurface soil
 - b) Ingestion of homegrown produce in native soil
2. Prevent or minimize exposure to volatile organic compounds (VOCs) in soil gas at concentrations that would pose unacceptable risk via indoor inhalation of vapors. *Table 7* of the final soil gas memorandum (ChaduxTt 2011) lists the volatile chemicals. This list includes semivolatile organic compounds (SVOCs) such as pesticides and polyaromatic hydrocarbons (PAHs). Remediation goals for VOCs to address exposure via indoor inhalation of vapors may be superseded based on chemical of concern (COC) identification information from future soil gas surveys. Future action levels would be established for soil gas, would be accounted for vapors from both soil and groundwater, and would be calculated based on a cumulative excess cancer risk level of 10^{-6} using the accepted methodology for risk assessments at HPNS.

Groundwater RAOs:

1. Prevent or minimize exposure to VOCs in the A-aquifer groundwater at concentrations above RGs via indoor inhalation of vapors from groundwater.
2. Prevent or minimize direct exposure to the groundwater that may contain COCs through the domestic use pathway in the B-aquifer, RU-C5 only (for example, drinking water or showering).
3. Prevent or minimize exposure of construction workers to metals and VOCs in the A-aquifer groundwater at concentrations above RGs from dermal exposure and inhalation of vapors from groundwater.
4. Prevent or minimize migration to the surface water of San Francisco Bay of chromium VI and zinc in the A-aquifer groundwater that would result in concentrations of chromium VI above 50 micrograms per liter ($\mu\text{g/L}$) and zinc above 81 $\mu\text{g/L}$ at the point of discharge to the bay.

The Parcel C RA work described herein was conducted per the selected remedy for nonradiological contaminants at Parcel C, described in the ROD for Parcel C (Navy 2010) as follows:

- Soil Remedy (S-5 in the ROD): The selected remedy for soil consists of excavation and off-site disposal, soil vapor extraction, durable covers, and institutional controls (ICs).

- Groundwater Remedy (GW-3B in the ROD): The selected remedy for groundwater includes treatment of VOCs with in situ ZVI or a biological substrate, monitored natural attenuation (MNA), and ICs.

1.3 Active Treatment Criteria for Groundwater

The following summarizes the active treatment criteria (ATC) for implementing specific remediation technologies for groundwater presented in the ROD (Navy 2010) and the RDDBR for Parcel C (KCH 2012). The groundwater ATC for in situ groundwater remediation in the A-aquifer are as follows:

- ZVI treatment will target hotspot areas where concentrations of tetrachloroethene (PCE) exceed 15 micrograms per liter ($\mu\text{g/L}$) or trichloroethene (TCE) exceeds 110 $\mu\text{g/L}$.
- Anaerobic in situ bioremediation (ISB) treatment will target areas where PCE is greater than 5.4 $\mu\text{g/L}$ but less than 15 $\mu\text{g/L}$, TCE is greater than 29 $\mu\text{g/L}$ but less than 110 $\mu\text{g/L}$, 1,2-dichloroethene (DCE) is greater than 2,100 $\mu\text{g/L}$, or vinyl chloride (VC) is greater than 25 $\mu\text{g/L}$.
- Aerobic ISB treatment will target areas where 1,4-dichlorobenzene (DCB) is greater than 21 $\mu\text{g/L}$ or chlorobenzene (CB) is greater than 3,900 $\mu\text{g/L}$.

Soil and groundwater RGs are presented in **Attachment 1**, and ATC for groundwater are summarized in **Table 1-2**.

1.4 Project Schedule

Table 1-3 summarizes the schedule for the preliminary remedial action (pre-RA) characterization and RA activities, including the performance monitoring.

1.5 Interim Remedial Action Completion Report Organization

This I-RACR is organized as follows:

- **Section 1.0: Introduction** – Provides an overview of the project, scope of work, regulatory framework, RGs and ATC for groundwater, project schedule, and organization of this I-RACR.
- **Section 2.0: Conceptual Site Model** – Presents a summary of the site description and history, previous investigations and RAs, a summary of the pre-RA characterization activities documented in the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**), an overview of Parcel C geology and hydrogeology, and nature and extent of contamination at RU-C1 and RU-C2.
- **Section 3.0: Field Implementation Activities** – Describes the field implementation activities, groundwater injection activities, deviations from the work plan, and waste characterization and disposal activities in support of the RA activities.
- **Section 4.0: RA Performance Monitoring Results** – Describes the in situ groundwater performance monitoring results for RU-C1-1 and RU-C2-3 A-aquifer.
- **Section 5.0: Conclusions and Recommendations** – Summarizes the groundwater treatment at RU-C1-1 and RU-C2-3 and provides recommendations for continuing post-RA monitoring.
- **Section 6.0: References** – Presents references used throughout this I-RACR.

Several supporting documents are presented as attachments and appendices to this RAWP, including:

Attachments:

Attachment 1 Remediation Goals (Parcel C ROD)

Appendices:

Appendix A Remedial Action Work Plan Addendum
Appendix B Geologic and Well Construction Logs
Appendix C Weekly Construction Quality Control Reports
Appendix D Photodocumentation
Appendix E Waste Manifests and Discharge Reports
Appendix F Remedial Action Land Survey Reports
Appendix G Groundwater Injection Implementation Reports
Appendix H Geo Tactical Report
Appendix I Field Documentation Forms
Appendix J Analytical Data and Field Parameters for RU-C1-1 and RU-C2-3 Baseline and Post-Remedial Action Events
Appendix K Performance Monitoring Trend Charts: RU-C1-1 and RU-C2-3
Appendix L Response to Comments (Placeholder)
Appendix M Remedial Action Laboratory Reports
Appendix N Remedial Action Data Validation Reports

2.0 CONCEPTUAL SITE MODEL

This section presents the Parcel C CSM with respect to site description and history, previous investigations and RAs, geology and hydrogeology overview, and nature and extent of COCs.

2.1 Site Description and History

This section provides the site description and a brief historical context for HPNS as described in the Final Feasibility Study (FS) (Sultech 2008). HPNS is located in the southeastern part of San Francisco on a long promontory that extends east into San Francisco Bay (**Figure 1-1**). HPNS comprises 934 acres: 491 acres on land and 443 acres underwater in the Bay. In 1940, the Navy obtained ownership of HPNS for shipbuilding, repair, and maintenance. After World War II, activities at HPNS shifted to submarine maintenance and repair. HPNS was also the site of the Naval Radiological Defense Laboratory. HPNS was deactivated in 1974 and remained relatively unused until 1976. Between 1976 and 1986, the Navy leased most of HPNS to Triple A Machine Shop, Inc., a private ship repair company. In 1987, the Navy resumed occupancy of HPNS.

HPNS property was placed on the National Priorities List (NPL) in 1989 pursuant to CERCLA because past shipyard operations had left hazardous substances on-site. In 1991, HPNS was designated for closure pursuant to the Defense Base Realignment and Closure Act of 1990. Closure at HPNS involved conducting environmental remediation and making the property available for nondefense use. To facilitate site cleanup and property transfer, HPNS was originally divided into six parcels, Parcels A through F. Parcels B, C, D, and E were subsequently subdivided further to assist with site cleanup and property transfer. Parcel B was subdivided into Parcels B-1 and B-2 and Sites IR-07 and IR-18 to accommodate varying property transfer schedules for different portions of the parcel. Parcel C was subdivided into Parcel C and Parcel UC-2 (**Figure 1-1**). Parcel D was subdivided into Parcel D-1 and D-2. Parcel E was subdivided into Parcel E and Parcel E-2. Parcel F is the offshore sediment area. Parcels A, D-2, UC-1, and UC-2 have been transferred to the San Francisco Redevelopment Agency (SFRA) and are no longer federal government property.

Parcel C is the oldest portion of the shipyard and has been used almost exclusively for industrial purposes since the late 1800s. Historically, the dominant land use of Parcel C was for shipping, ship repair, office, and commercial activities. According to the amended Hunters Point Shipyard Redevelopment Plan (SFRA 2018), Parcel C is expected to be zoned for office and industrial uses, multimedia and digital art uses, hotels, institutional uses, retail sales and services, residential services, residential dwellings, arts and entertainment, civic uses, parks and recreation, and open space.

Parcel C historically included approximately 79 acres in the central portion of the shipyard. In 1997 and 2002, the boundaries of Parcels B and C were redefined. In 2008, the Navy divided Parcel C into two new parcels: Parcel C and Parcel UC-2, which lies west of the revised Parcel C (**Figure 1-1**). The current Parcel C comprises approximately 73 acres and includes four RUs (RU-C1, RU-C2, RU-C4, and RU-C5 as shown in **Figure 1-2**).

Parcel C is bounded on the east by the Bay, on the south by Berths 8 and 9, on the southwest by Dry Dock 4, and on the west by Fisher Avenue (**Figure 1-1**). Transfer to the City of San Francisco and development of Parcel C are scheduled to begin in 2020. COCs at Parcel C include VOCs, PAHs, polychlorinated biphenyls (PCBs), carbon tetrachloride (CT), and metals. The Final ROD for Parcel C was signed in September 2010 (Navy 2010).

The Final FS also contains a description of geographic units associated with CERCLA actions and proposed redevelopment blocks as defined by the SFRA in 1997 and amended in 2010, as incorporated in the RDDBR (KCH 2012).

2.2 Previous Investigations and Remedial Actions

The overall investigative history of Parcel C, including both CERCLA and non-CERCLA activities, is summarized in *Table 1* of the Final Parcel C ROD (Navy 2010) and the RDDBR (KCH 2012). Key references for Parcel C, particularly for RU-C1 and RU-C2 are:

- 2008 – Final FS Report for Parcel C, Hunters Point Shipyard (Sultech 2008)
- 2010 – Final ROD for Parcel C, Hunter Point Naval Shipyard (Navy 2010)
- 2012 – Pre-Design Investigation Technical Memorandum RU-C2, Parcel C, Hunters Point Naval Shipyard (Alliance Compliance Group Joint Venture [Alliance] 2012)
- 2012 – Final Remedial Design and Design Basis Report for Parcel C, Hunters Point Naval Shipyard (KCH 2012)
- 2012 – Final Treatability Study Completion Report, RU-C5, Hunters Point Naval Shipyard (CDM Smith 2012)
- 2013 – Final Remedial Action Work Plan RU-C2, Hunters Point Naval Shipyard (Alliance 2013)
- 2013 – Final Work Plan, Parcel C Remedial Action, RUs C1, C4, and C5, and Building 241 (Excludes C2) (CB&I 2013)
- 2015 – Remedial Actions completed in RU-C2, updates from the Navy
- 2015 – Final Work Plan Addendum 01, Parcel C Remedial Action RUs C1, C4, and C5, and Building 241 (Excludes C2) (CB&I 2015c)
- 2017 – Final Remedial Action Work Plan Parcel C RUs C1, C2, C4, and C5, (ECC-Insight and CDM Smith 2017)
- 2018 – Final Interim Remedial Action Completion Report (I-RACR) Parcel C RUs C1, C4, and C5, and Building 241 (Exclude C2) (Aptim Federal Services, LLC [APTIM] 2018)
- 2019 – Final Remedial Action Work Plan Addendum Parcel C RUs C1, C2, C4, and C5 (ECC-Insight and CDM Smith 2019a; **Appendix A**)
- 2019 – Final Parcel C Soil Vapor Extraction System Operation and Maintenance Summary Report (ECC-Insight and CDM Smith 2019b)
- 2019 – Data from the Basewide Groundwater Monitoring Program (BGMP) (Trevet 2019)

Numerous previous and ongoing characterization and RAs have been conducted at Parcel C. **Table 1-1** summarizes the most recent RAs for Parcel C.

2.3. RU-C1 and RU-C2 Pre-RA Characterization Summary

RU-C1 and RU-C2 pre-RA field characterization activities were conducted over two mobilizations between November 2017 and July 2018. Details including number of samples, analytical results, and field data are summarized in **Appendix A**, which was previously reviewed and finalized with BCT review as part of the

RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**). The pre-RA characterization activities for soil and groundwater, the updated CSM, and a summary of the proposed RA were identified for the following areas (**Figure 1-2**).

1. **RU-C1:** RU-C1-1 and RU-C1-3/Building 253 groundwater plumes
2. **RU-C2:** Building 251, Excavation 20B-1 and RU-C2-1 B-aquifer groundwater plume and RU-C2-3 groundwater plume

A 3-D visualization model (Leapfrog Works®) was used to visualize the geologic stratigraphic units, distribution of COCs, estimate COC-impacted areas, and refine the RA treatment area lateral and vertical extent. The following summarizes the highlights of the pre-RA characterization for RU-C1 and RU-C2, which was used to update the CSM and develop RAs for groundwater impacted with COCs above ATC at RU-C1-1 and RU-C2-3 (**Sections 3 and 4**) in accordance with the ROD (Navy 2010). In accordance with the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**) recommendations, additional RAs are planned for Excavation 20B-1 and RU-C1-3 under separate Navy contracts.

2.3.1 RU-C1 pre-RA Characterization Summary

Pre-RA characterization activities were conducted for RU-C1-1 and RU-C1-3, as detailed in **Appendix A** (ECC-Insight and CDM Smith 2019a). The following is a summary of the findings.

RU-C1-1. Per the RAWP objectives (ECC-Insight and CDM Smith 2017), the lateral and vertical extent of COCs exceeding the groundwater ATC for RU-C1-1 were characterized (**Table 2-1b, Figures 2-1, 2-2 and 2-3, Appendix A**). Details on the nature and extent of COCs are provided in **Section 2.5**. As part of this I-RACR, a RA was implemented in RU-C1-1 to address groundwater ATC exceedances as described in **Section 3**.

RU-C1-3. Per the RAWP objectives (ECC-Insight and CDM Smith 2017), the lateral and vertical extent of COCs exceeding the groundwater ATC for RU-C1-3 were characterized (**Appendix A Table 3-4**). RU-C1-3 evaluation extended to the former solvent sumps under the former paint room in Building 253 and to Building 211 (see **Appendix A Tables 3-2, 3-3 and 3-4 and Appendix A Figure 3-8**). The pre-RA characterization results for groundwater at RU-C1-3 and the area of the former solvent sumps in Building 253 are as follows:

1. PCE, TCE, cis-1,2-DCE, and VC persist near the former paint room; the VC plume is the most extensive in groundwater (see **Appendix A Figure 3-10**).
2. Dense non-aqueous phase liquid (DNAPL) was observed in soil boring RUC13SB14, located in the center of the former paint room, during pre-RA characterization at a depth of 18 to 20 feet below ground surface (bgs), atop the Bay Mud (see **Appendix A Figures 3-9a, 3-9b, 3-9c, and 3-10**). The DNAPL sample was composed of TCE, cis-1,2-DCE, diesel, and motor oil, which is consistent with the COCs present in the groundwater plume (**Appendix A, Table 3-2**).
3. Substantial anaerobic attenuation of TCE is occurring in the dissolved phase plume at RU-C1-3 (see **Appendix A Section 4.3.2**), as indicated by the presence of reductive dechlorination (RD) products cis-1,2-DCE, VC, ethene, and ethane. TCE is only observed in the area near the former paint room, likely associated with the presence of residual DNAPL.
4. Light non-aqueous phase liquid (LNAPL) was observed and measured in well IR28MW557A, located beneath the sump area and in the footprint of Corrective Action Area (CAA)-14. Total petroleum hydrocarbons (TPH) was reported in borings beneath the sump area. The comingled

TPH is likely facilitating the significant anaerobic chlorinated VOC attenuation observed by providing carbon and electrons to dechlorinating bacteria.

5. Geochemical data collected during baseline groundwater sampling (**Appendix A**), indicate that reducing conditions typical of sulfate reduction and methanogenesis are present in the groundwater at RU-C1-3. Anaerobic conditions promote RD of TCE to ethene/ethane.
6. The presence of DNAPL provides a continuous long-term source of COCs to groundwater at RU-C1-3.

As documented in the RAWPA (**Appendix A**), remedial options will be further evaluated to address the DNAPL source area that will include treating the RU-C1-3 dissolved phase plume. The Navy will prepare a separate work plan for stakeholder review that proposes RA options to treat the DNAPL source area and subsequently the associated groundwater plume at RU-C1-3.

2.3.2 RU-C2 Pre-RA Characterization Summary

RU-C2 pre-RA characterization activities were conducted at Building 251, Excavation 20B-1, RU-C2-1 (B-aquifer), and RU-C2-3 fractured water-bearing zone (F-WBZ) as detailed in **Appendix A** (ECC-Insight and CDM Smith 2019a). The following is a summary of the findings.

Building 251, Excavation 20B-1. An excavation was conducted in Building 251, Excavation 20B-1, in 2013 and 2014 by Alliance Compliance Group Joint Venture (Alliance 2015), with dimensions of approximately 53 feet by 34 feet, as determined from the survey of the asphalt cap, and extended to approximately 5 to 10 feet deep. The excavation was backfilled with sand, silty sand, and some gravel, based upon lithologic logging of soil from borings within the former excavation. As described in the RDDBR (KCH 2012), for excavations under buildings (such as Excavation 20B-1), the maximum excavation depth is 10 feet bgs. Therefore, as part of the pre-RA detailed in the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**), 39 borings were advanced to delineate the lateral and vertical extent of COCs and evaluate the extent of potential groundwater sources (**Appendix A Table 3-7, Figure 2-6; Figure 3-19**). In addition, per BCT comments, an additional 4 soil borings were advanced to the north of the Building 251, and those results are included in **Appendix J** (see **Appendix J-3** and **Figure J-3**). COCs in soil at Building 251 include VOCs (primarily dichlorobenzenes), PCBs, PAHs, metals, and TPH (Navy 2010; Sultech 2008). The pre-RA characterization provided sufficient data to understand the nature and extent of soil COCs in and around the area of Building 251 Excavation 20B-1. Pre-RA characterization results indicated COCs in soil with potential for non-aqueous phase liquid (LNAPL and DNAPL), a potential source for groundwater contamination.

In a deviation from the RAWP and as identified in the RAWPA (**Appendix A**), the RA for Excavation 20B-1 was postponed because of the complexity in the shoring design that would be required to conduct the excavation safely and maintain the integrity of Building 251. The Navy is preparing a separate work plan for stakeholder review to address Excavation 20B-1.

RU-C2-1 Plume (B-aquifer). In RU-C2-1, PCE is present in the deeper interval of the B-aquifer in sediments above the fractured bedrock. 1,4-DCB and CT also have been detected in localized areas in the B-aquifer in RU-C2-1 (**Appendix A Figure 3-20**). Data from previous investigations, summarized in the Final FS (Sultech 2008), had indicated that the A- and B-aquifers may be hydraulically connected because of the absence of the Bay Mud aquitard and that B-aquifer contamination may serve as a source of COCs to the A-aquifer. However, results from this pre-RA characterization identified and delineated a Sandy Lean Clay aquitard below RU-C2-1 that is located at a similar depth elevation as the Bay Mud in RU-C1 and is continuous across RU-C2-1 area, except where it was removed during previous excavations (**Appendix A**

Figures 3-1a, 3-1b, 3-1c, 3-11, 3-12, and 3-13). Geotechnical and hydraulic evaluation of this unit confirms that it acts as a hydraulic barrier between the A- and B-aquifers with permeability values between 10^{-9} and 10^{-6} centimeters per second (cm/s) (**Appendix A Table 3-5**). Therefore, in a deviation from the RAWP (ECC-Insight and CDM Smith 2017), active groundwater treatment for the B-aquifer PCE plume was no longer proposed, consistent with the RAOs established for Parcel C ROD (Navy 2010). However, per BCT request, two new B-aquifer monitoring wells (RUC2MW15B and RUC2MW16B) were installed during field activities in the eastern portion of the PCE footprint to further define the plume and support long-term monitoring of the B-aquifer plume (see **Section 3.4.2**). Analytical data results and a location map are presented in **Appendix J (Appendix J-2, Figure J-2)**.

RU-C2-3 Plume (F-WBZ). PCE, CT, and TCE are the COCs in groundwater at RU-C2-3 that exceed the ATC (**Table 2-2, Figures 2-2, 2-4, 2-5**). As discussed in **Appendix A** and **Section 2.6**, groundwater flow within RU-C2-3 is limited to preferential pathways within zones of less competent bedrock and fractures. The TCE and CT plume associated with the RU-C2-3 source was delineated vertically and laterally during the pre-RA characterization efforts. The comingled plume resulted in adjustments to the remedial approach as documented in the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**). The refined RA for RU-C2-3 combines ZVI and ISB amendment emplaced throughout the COC plume at target treatment depths of 12 to 29 feet bgs, as summarized in **Section 3**.

2.4 Overview of Parcel C Geology and Hydrogeology

This section provides a summary of the Parcel C geology and hydrogeology, summarized from the FS (Sultech 2008), the RAWP (ECC-Insight and CDM Smith 2017), and RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**). This section also includes updates to the stratigraphic units present at Parcel C. Historical maps and aerial photographs were reviewed to supplement the field investigation observations, as described below. **Figure 2-6** provides a ground surface geologic map of Parcel C.

2.4.1 Geology

Prior to the 1900s, the topographic surface of Parcel C consisted of bedrock highlands with steep cliffs that terminated at the Bay shoreline (PRC Environmental Management, Inc. [PRC] 1997). An 1859 trigonometrical survey of the U.S. Coast Survey Office shows the HPNS coastline prior to artificial fill (U.S. Coast Survey Office 1859). During the early 1900s, artificial fill derived partially from the bedrock was emplaced on the south side of Dry Dock 2 to form the southeastern shoreline until 1942 (Sultech 2008). Aerial imagery from 1938 showed a seawall running along the approximate orientation of Robinson Drive near Building 214 and terminating near Building 253 at a riprap shoreline. After 1942, the bedrock highlands in the west were blasted to near sea level and a second phase of filling and grading began, which resulted in extending the land surface to the current shoreline (**Figure 2-6**).

The bedrock geology consists primarily of easterly dipping basement rocks of the Franciscan Complex unconformably overlain by naturally occurring depositional sediments, quaternary alluvium, and artificial fill (Bonilla 1998). The naturally occurring depositional sediments consist of Sandy Lean Clays (QtF), Undifferentiated Upper Sands (Quus), Bay Mud (Qbm), and Undifferentiated Sediments (Qu) at Parcel C. These units are summarized below from youngest to oldest (**Figure 2-6**).

Artificial Fill (Qaf): The Artificial Fill consists of a heterogeneous mixture of unconsolidated material derived from many sources, which are mostly undocumented, and is typically the first encountered stratigraphic unit. The fill thickness ranges from approximately 2 feet in the western end of RU-C2 to 25 feet in the southeast portion of RU-C1. The sources of the fill consist of quarried bedrock from the adjacent upland areas, dredged marshland deposits, industrial fill, building debris, and riprap. The quarried bedrock

fill consists of serpentinite, which contains naturally occurring minerals with asbestos, arsenic, manganese, nickel, and other metals (Sultech 2008; APTIM 2018; **Figure 2-6**).

Undifferentiated Upper Sands (Quus): The Quus consist of poorly graded, discontinuous conforming estuarine and alluvial sand deposits that are interfingering with the Bay Mud or Sandy Lean Clay. These sand deposits represent naturally occurring beach or alluvial deposits that were deposited along the relict shoreline at varying sea levels.

Bay Mud (Qbm): The Bay Mud consists of dark greenish/bluish gray fine-grained Holocene estuarine sediments that are predominantly composed of silt and clay but may include lenses of clayey or silty sands. The Bay Mud is rich in organic content and contains localized deposits of shell fragments and plant matter. The Bay Mud may underlie either artificial fill or upper sand deposits and may overlie the deeper Undifferentiated Sediments.

Sandy Lean Clay (Qtff): The Sandy Lean Clay consists of a thin layer of naturally occurring low permeability Tidal Flat Deposit and clayey sand with a high organic content and low plasticity. It is generally dark yellowish brown to dark brown. The Sandy Lean Clay accumulated along the relict, pre-1900 ground surface during depositional periods when low-energy tidal water would inundate a narrow strip of land between the bedrock highlands in the west and in the northeast (near Dry Docks 2 and 3) (U.S. Coast Survey Office 1859). The Bay Mud grades into the Sandy Lean Clay moving west (inland) from RU-C1 toward RU-C2 as exemplified by a potential transition zone on the eastern edge of Building 251 where Bay Mud and Sandy Lean Clay are identified in borings. The Sandy Lean Clay is present across most of RU-C2 and contacts the dipping bedrock in the vicinity of Building 251. The deposit is absent only in a small portion of RU-C2, north of Building 251, where previous excavation activities incidentally removed a small portion of the Sandy Lean Clay in the footprint of the former underground storage tanks and solvent sumps (see **Appendix A Figures 3-15 and 3-18**).

Undifferentiated Sediments (Qu): The Undifferentiated Sediments is an unconsolidated Pleistocene formation consisting of alluvial sands, silts, or clays that lie unconformably over the underlying Franciscan Complex Bedrock. This unit represents a wide range of nonmarine derived sediments and is likely associated with the Undifferentiated San Antonio Formation, which is typically found along the margins of the Bay where younger Bay Mud deposits pinch out (Rogers and Figuers 1991). This unit is generally found at Parcel C where bedrock is deeper than 30 feet bgs (–20 feet above mean sea level [amsl]) and generally absent in areas of shallower bedrock, such as at RU-C2-3.

Franciscan Complex Bedrock (Kf): The Cretaceous Franciscan Complex is a mix of igneous, sedimentary, and metamorphic rocks assembled during subduction-related continental-margin accretion. The complex's rock types include weathered serpentinite (Kf-sp), sandstone and shale (Kf-s), greenstone (Kf-g), and radiolarian chert (Kf-c) (**Figure 2-6**). Bedrock competency is variable, with fractures commonly present in the weathered layers. The bedrock surface elevation is shown in **Figure 2-7**.

Weathered Franciscan Chert (Kf-c) – Lean Clay (Kf-CL): The Weathered Franciscan Chert is a highly weathered residual subunit of the Franciscan Complex Bedrock, consisting of angular chert gravel with a high clay content. This subunit occurs at the surface of the bedrock along the southern end of RU-C2 and forms a wedge-shaped block if viewed in cross section, up to 20 feet thick and becomes thicker to the south (**Figures 2-6**).

The complex structure of the subsurface lithology at Parcel C has resulted in a variety of factors influencing COC distribution. Each RU has a specific set of geologic conditions that influence the COC distribution and transport, groundwater advection, and potential impacts to receptors. Therefore, a detailed

understanding of the geologic units was developed to support decisions on implementing RAs for each RU area.

2.4.2 Hydrogeology

This section presents an overview of hydrogeology at Parcel C as previously described during recent characterization activities (ECC-Insight and CDM Smith 2019a; **Appendix A**). RU-specific details on the hydrogeology at RU-C1 and RU-C2 are provided in the subsequent sections. Generally, Parcel C contains three primary water-bearing zones (A-aquifer, B-aquifer, F-WBZ) and fine-grained confining units as described as follows:

A-aquifer: At Parcel C, the A-aquifer is found almost exclusively within the Artificial Fill geologic unit but also is locally present in alluvium, colluvium, Quss, and shallow bedrock (Sultech 2008). The hydraulic conductivity calculated from A-aquifer testing, as reported in the remedial investigation report, ranges from approximately 10^{-7} cm/s to 10^{-1} cm/s (PRC 1997; Fetter 2001). The potentiometric surface of the A-aquifer is shown in **Figure 2-8**. The overall groundwater flow direction in the A-aquifer is generally from the west-northwest to the east-southeast and flows from a topographic high located near RU-C5 toward the Bay near RU-C1. The average horizontal gradient across much of Parcel C is relatively flat with an average value of approximately 0.004 foot/foot over 1,000 feet. Because of the relatively flat potentiometric surface and generally anisotropic conditions, the local groundwater flow direction and magnitude is primarily controlled by preferential pathways of high permeability materials and less by the potentiometric head. Within RU-C2-3, the F-WBZ is close to the ground surface and so is included in the A-aquifer.

Bay Mud/Sandy Lean Clay Confining Units: The Bay Mud unit occurs throughout RU-C1 and is a confining layer separating groundwater in the A-aquifer and B-aquifer. Based on the boring logs for monitoring wells installed in the B-aquifer at RU-C1-1, the Bay Mud is approximately 5 feet thick at this area. At RU-C2-1, the Sandy Lean Clay, which is approximately 5 to 12 feet thick, separates the A-aquifer and B-aquifer. Geotechnical analyses performed on samples from the Sandy Lean Clay indicated a range of permeability values between 10^{-9} and 10^{-6} cm/s, which are consistent with clays or clay-like material typically classified as a confining layer (Fetter 2001). Therefore, the Sandy Lean Clay serves as a confining layer between the A-aquifer and B-aquifer when the Bay Mud is absent. The Bay Mud and Sandy Lean Clay occur at similar elevations across Parcel C and the Bay Mud appears to transition into the Sandy Lean Clay.

B-aquifer: The B-aquifer is only present in the south-central portion of Parcel C and covers approximately 17.5 acres within RU-C1, and portions of RU-C2, RU-C4, and RU-C5. In RU-C2-3, particularly near Building 258, the B-aquifer is absent and the F-WBZ is close to the surface. In this area, the F-WBZ is included in the A-aquifer. The B-aquifer consists of sand and silty sand of the Undifferentiated Sediment deposits. The B-aquifer is generally separated from the A-aquifer by the Bay Mud or the Sandy Lean Clay. The bottom of the B-aquifer is defined by the bedrock/alluvium interface. At Parcel C, the B-aquifer is likely semiconfined because the top of the aquifer is confined by the Sandy Lean Clay or Bay Mud, but the bottom of the aquifer is bounded by the Franciscan Bedrock Complex. Because the Franciscan Bedrock Complex includes weathered zones of fractured rock, recharge of the B-aquifer could occur where the F-WBZ is in direct contact with the B-aquifer. The hydraulic conductivity calculated from B-aquifer testing, as reported in the remedial investigation report (PRC 1997), ranges from approximately 10^{-5} cm/s to 10^{-4} cm/s, which corresponds to materials ranging from silty sand to poorly graded sand (PRC 1997; Fetter 2001). Generally, groundwater flow direction in the B-aquifer is west to east across Parcel C.

Weathered Franciscan Chert – Lean Clay Confining Unit: This unit has been identified within highly weathered zones within the chert subunit of the Franciscan Formation (e.g., the southern end of RU-C2). It

has a relatively low permeability based on the presence of a high clay content and low recharge rates in temporary wells completed in this unit. The presence of the clay unit primarily affects groundwater migration by diverting groundwater to more permeable bedrock weathering zones.

Fractured Water-Bearing Zone: The F-WBZ consists of groundwater present within fractures of the Franciscan Complex Bedrock. The hydraulic conductivity calculated from F-WBZ aquifer testing, as reported in the remedial investigation report (PRC 1997), ranges from approximately 10^{-7} cm/s to 10^{-2} cm/s. Flow conditions range from laminar seepage to sheet flow. Groundwater flow in the F-WBZ is dependent on the degree and connectiveness of fractures, fracture orientation, weathering, and secondary precipitation of minerals in fractures. The F-WBZ is not considered an aquifer because of its low capacity for water production. The upper F-WBZ is generally considered part of the overlying hydrostratigraphic unit (either the A- or B-aquifer, whichever overlies the F-WBZ). At RU-C2-3, the A-aquifer is largely in an upper weathered F-WBZ.

2.4.3 Groundwater Gradient and Flow Characteristics

Groundwater flow at Parcel C varies significantly depending on the hydrostratigraphic unit (i.e., A-aquifer, B-aquifer, or F-WBZ) and within different areas of interest. The horizontal groundwater flow was evaluated in a synoptic 2018 groundwater water level measurement event at RU-C1 and RU-C2 (ECC-Insight and CDM Smith 2019a; **Appendix A**) with the potentiometric surface generated shown on **Figure 2-8**. Groundwater elevations at Parcel C typically range from 0 to 10 feet above mean sea level. Depth to top of the A-aquifer occurs at approximately 8 to 10 feet bgs. Groundwater elevations in the A-aquifer are influenced by tidal fluctuations that create a sinusoidal pressure wave near the shoreline. Tidal influence in the A-aquifer decreases with increasing distance from the shoreline. At HPNS, the mean tidal range (calculated as the difference in height between mean high water and mean low water) is approximately 5 feet, and the maximum tidal range is approximately 10 feet. A Tidally Influenced Zone has been delineated for the A-aquifer, defined as the location where tides cause groundwater elevations to fluctuate by 0.1 feet or more. The width of this Tidally Influenced Zone varies from approximately 75 to 500 feet along the shoreline (not considering the concrete dry docks, which are hydraulically separated from the groundwater by the dock wall).

Groundwater flow patterns at HPNS are influenced by the upgradient Parcel A topographic high, which is west of Parcel C, with a general radial pattern of groundwater flow away from Parcel A toward the shoreline. The principal sources of groundwater recharge for the A-aquifer at Parcel C are considered horizontal groundwater flow from areas upgradient of Parcel C (lateral influx) and minor precipitation infiltration since the durable cover was placed. At Parcel C, the general direction of groundwater flow is to the east where groundwater discharges into the Bay. Locally, at Bay-side perimeter locations of the Parcel, the groundwater flow direction is southeast or northeast directly toward the Bay.

The semiconfined B-aquifer is present beneath central portions of Parcel C. Groundwater elevation data for the B-aquifer at Parcel C indicate groundwater flows toward the east, south, and southeast. The primary source of groundwater recharge to the B-aquifer at Parcel C is horizontal groundwater flow from upgradient areas (lateral influx). At areas where the Bay Mud or Sandy Lean Clay aquitard is nonexistent, recharge to the B-aquifer also may come from the overlying A-aquifer, particularly when infiltration from precipitation recharges the A-aquifer. Based on potentiometric surface maps developed as part of the BGMP, groundwater flow from the B-aquifer in the central area of Parcel C is east toward the Bay.

Only the F-WBZ with overlying fill material exists in upgradient areas (within several hundred feet of the former Parcel A) with areas observed in RU-C2 and RU-C4. The upgradient F-WBZ groundwater flows

laterally into the A- or B-aquifers. Discharge from the A-aquifer occurs principally as lateral flow of groundwater to the Bay (lateral outflux) at the shore.

Depending on the vertical component of groundwater flow, the F-WBZ at a particular location may be recharged by or discharge to either the A- or B- aquifers. Discharge from the F-WBZ is to the A- and B-aquifers and to the Bay. In Parcel C, groundwater elevations in monitoring wells in the semiconfined B-aquifer and in the F-WBZ can be up to several feet higher than in nearby A-aquifer monitoring wells, suggesting vertical gradients and the potential for upward flow from deeper aquifers to the A-aquifer where the Bay Mud or the Sandy Lean Clay aquitard is absent.

2.5 RU-C1-1 Groundwater Plume

This section summarizes the nature and extent of COCs for RU-C1-1 where the groundwater RA was conducted.

2.5.1 RU-C1-1 Hydrogeology

RU-C1 is in the eastern area of Parcel C and includes RU-C1-1 (Building 231) and RU-C1-3 (Buildings 253 and 211). The primary lithologic units associated with the RU-C1-1 groundwater plume consist of Qaf and the Qbm confining layer. The A-aquifer saturates the Artificial Fill with a thickness of approximately 5 to 12 feet bgs (5 to –8 feet amsl) depending upon the elevation of the water table. Approximately 5 feet of the Bay Mud confining unit extends beneath the A-aquifer, separating it from the underlying B-aquifer, as determined from the well construction logs for IR28MW557B and IR28MW400B. The elevation of the Artificial Fill/Bay Mud contact dips to the south across RU-C1-1; the depth to Bay Mud at IR28MW557B is 12.75 feet bgs (–2.48 feet amsl) to the north of RU-C1-1. To the south of RU-C1-1, the depth to the Artificial Fill/Bay Mud contact is 20 to 23 feet bgs (–10.91 to –13.91 feet amsl; **Figure 2-3**).

Groundwater elevations in the A-aquifer range from 4.35 feet amsl at well IR28MW128A to 3.32 feet amsl at well IR28MW122A in June 2018 (**Figure 2-8**). The horizontal hydraulic gradient of the A-aquifer in RU-C1-1 is approximately 0.0004 foot/foot in the southeast direction dropping off to a gradient of 0.005 foot/foot along the margin of the Bay.

2.5.2 RU-C1-1 Nature and Extent of COCs

The pre-RA characterization indicated that PCE is present above the ATC at only one location: RUC11HPT04 (**Table 2-1; Figures 2-1 and 2-3**), which was detected at 87 µg/L at RUC11HPT04 between 9 and 13 feet bgs (2.8 to –1.2 feet amsl). Two step-out borings (RUC11SB05 and RUC11SB06) were advanced in June 2018 to bound the southeastern portion of the plume and COCs were below ATC at both borings. The vertical extent of PCE is bounded by the Bay Mud. In addition, one new monitoring well was installed to assist with the performance monitoring at RU-C1-1 and to bound the COC plume to the west: IR28MW938A (**Figures 2-1 and 2-3**). Monitoring well construction details are presented in **Appendix B**.

2.6 RU-C2-3 Groundwater Plume

This section presents updates to the CSM, as developed in the RAWP (ECC-Insight and CDM Smith 2017) for hydrogeology and the nature and extent of COCs in groundwater at RU-C2-3. The primary source area for the RU-C2-3 plume is the Building 258 pipe manufacturing facility where degreasing solvents were used, including a former open pickling and degreasing operation between Buildings 258 and 251. These activities resulted in releases of chemicals to the subsurface during historical operations. COCs in groundwater at RU-C2-3, Building 258 include CT and TCE (ECC-Insight and CDM Smith 2017; **Appendix A**).

2.6.1 RU-C2-3 Hydrogeology

The lithology underlying RU-C2-3 consists of a thin layer of Artificial Fill overlying fractured Franciscan Bedrock. The surface of the bedrock ranges from 3 to 13 feet bgs (10 to 0 feet amsl) and dips steeply to the east-southeast away from Building 258 towards Building 251. Rock types of Franciscan Bedrock include weathered serpentinite, sandstone, shale, greenstone, and radiolarian chert (**Figure 2-6**). Bedrock competency is variable with intervals of fractures in the weathered portion of the bedrock. The bedrock F-WBZ consists of groundwater present within fractures of the Franciscan (Kf) bedrock. Groundwater flow is limited to preferential pathways within zones of less competent bedrock and fractures. Additionally, the Kf-CL subunit serves as a relatively impervious boundary that prevents groundwater from flowing to the southeast in RU-C2-3 and influences groundwater flow direction toward RU-C2-1 to the east-northeast. Downgradient of RU-C2-3, groundwater from the F-WBZ appears to be discharging into the B-aquifer near the western end of RU-C2-1 along the bedrock/sediment interface (see **Appendix A Figures 3-11 and 3-12**). There does not appear to be a direct pathway for groundwater flow from the F-WBZ to the A-aquifer.

2.6.2 RU-C2-3 Nature and Extent of COCs

The pre-RA characterization focused on delineating COCs (TCE and CT) in groundwater in the F-WBZ at RU-C2-3. The lateral extent of the groundwater plumes with COC concentrations that exceed ATC are shown in **Figure 2-4**. The TCE and CT plumes overlap on the east side of Building 258. TCE was above the active ZVI treatment criteria (29 µg/L) at RUC23SB02 (43 µg/L), RUC23SB03 (1,500 µg/L), RUC23SB04 (78 µg/L), RUC23SB08 (130 µg/L), RUC23SB09 (970 µg/L), RUC23SB12 (30 µg/L), and RUC23SB13 (44 µg/L). CT concentrations were above active treatment criteria (5 µg/L) at each location except RUC23SB02 and RUC23SB03 with the greatest concentration of CT was at RUC23SB08 (140 µg/L). Both plumes emanate from the area outside Building 258 where pickling and degreasing operations occurred. In addition, three new monitoring wells were installed to assist with the performance monitoring at RU-C2-3 IR28MW939F, IR28MW940F, and IR28MW941F (**Figure 2-4**). Baseline groundwater monitoring results for IR28MW941F identified TCE at 7,800 µg/L (**Figure 2-4**). IR28MW941F is located adjacent and south of RUC23SB03 (**Figure 2-4**). The vertical boundary for the COC plume is where the F-WBZ transitions to more competent, and dry, bedrock, at approximately 29 feet bgs (–16 feet amsl) (**Figure 2-5**). Monitoring well construction details are presented in **Appendix B**. Other COCs, without active treatment criteria, exceeding the residential RG in groundwater grab samples at RU-C2-3 included:

- 1,2-dichloroethane
- chloroform
- trichlorofluoromethane

2.7 Degradation of COCs

The primary groundwater COCs at RU-C1-1 are chlorinated ethenes and at RUC2-3 are chlorinated ethenes and methanes. Active treatment of these COCs relies on injection of amendments that degrade these chemicals through abiotic (ZVI) or biotic (ISB) mechanism(s). ZVI-catalyzed abiotic reduction occurs through beta elimination reactions, resulting in transformation of PCE and TCE to ethene and ethane. ZVI is also known to promote the reduction of CT (Matheson and Tratnyek 1994) to chloroform and lesser chlorinated compounds that are more susceptible to biotic degradation (Grostern et al. 2010; Justicia-Leon et al. 2012). Metal-mediated abiotic reduction is a function of redox conditions, temperature, and pH.

Biotic degradation of COCs is a function of geochemical conditions suitable for specific reactions, the availability of carbon and nutrients for microorganisms, and the presence of COC-degrading microbial

populations. During biotic degradation, microorganisms break down COCs through four primary mechanisms: oxidation, reduction, fermentation, or co-metabolism. The feasibility of these reactions is dictated by geochemical conditions and microbial population dynamics. Therefore, sufficient geochemical data are required to understand the geochemical setting and interpret degradation in different redox zones (i.e., aerobic or anaerobic).

Under aerobic conditions, oxygen is present as the primary electron acceptor and inhibits anaerobic bacteria (and reactions). Oxygen has a relatively low solubility (approximately 8 milligrams per liter [mg/L]), so if significant carbon is present in the aquifer, oxygen is quickly depleted and anaerobic processes predominate (e.g., fermentation; nitrate-, iron- and manganese-, and sulfate reduction and methanogenesis). Under aerobic conditions, COCs can act as a source of carbon and electrons (i.e., electron donor) coupled to oxygen in microbial metabolism, often resulting in breakdown to carbon dioxide and water.

Under anaerobic conditions, COCs can act as a source of carbon and electrons in microbial metabolism in fermentation reactions or coupled to nitrate-, iron-, manganese-, and sulfate reduction and carbon dioxide respiration (producing methane). In addition, COCs can act as alternate electron acceptors in microbial metabolism, which is common for many chlorinated chemicals (e.g., PCE, TCE), a process termed halorespiration, resulting in RD of chlorinated chemicals. Co-metabolic reactions can occur both aerobically and anaerobically if nonspecific enzymes or cofactors are produced, which break down COCs in reactions that provide no benefit to the microorganism. A summary of biotic aerobic and anaerobic degradation reactions for COCs at Parcel C are summarized below.

Chlorinated Ethenes. Under the appropriate biogeochemical and microbiological conditions, parent chlorinated ethenes, PCE and TCE, and their degradation daughter products may be amenable to several biotic attenuation mechanisms, including RD, aerobic oxidation, anaerobic oxidation, and co-metabolism. **Figure 2-9** shows the documented degradation pathways for PCE, TCE, cis-DCE, and VC under anaerobic and aerobic conditions. For chlorinated ethenes, particularly the higher chlorinated compounds such as PCE and TCE, the primary biotic degradation pathway is anaerobic (i.e., without oxygen) transformation via RD, with sequential transformation from PCE to TCE to cis-1,2-DCE (primary) or trans-1,2-DCE, VC, ethene, or ethane and chloride. Under aerobic conditions (i.e., in the presence of oxygen), PCE is largely recalcitrant and TCE is only biotically degraded under conditions that facilitate aerobic co-metabolism (ACM). ACM can be significant for TCE in redox transition zones where anaerobic and aerobic conditions are present. Often compounds that stimulate ACM, such as methane, ethane, ethene, propane or aromatics (i.e., benzene, toluene, phenol), or ammonia, are present with the chlorinated solvents and induce the enzymes that fortuitously degrade TCE, cis-1,2- or trans-1,2-DCE, or VC.

Other degradation mechanisms for the lower chlorinated ethenes and ethanes, such as trans-1,2-DCE, cis-1,2-DCE, and VC, include anaerobic direct metabolism (ANDM) coupled to sulfate or iron reduction and aerobic direct metabolism (ADM) (i.e., use as a food source for aerobic microorganisms), generating carbon dioxide and water (**Figure 2-9**). These alternate degradation mechanisms are important when there is significant sulfate or iron available anaerobically or in redox transitions zones where anaerobic groundwater encounters aerobic groundwater in the downgradient/distal plumes or periodic infiltration of aerobic precipitation during rain events. This can occur either down- or cross-gradient from the anaerobic source zone or below the anaerobic treatment zone if there is a vertical gradient resulting in vertical mixing with aerobic groundwater. In addition to the chlorinated ethenes, reductive daughter products ethene and ethane can be oxidized (i.e., used as food sources) by aerobic or anaerobic sulfate- or iron-reducing microorganisms. Under conditions where reductive daughter products are being directly metabolized, a complete mass balance is not possible.

Chlorinated Methanes. CT is recalcitrant under aerobic conditions, with no known degradation pathway reported. Under anaerobic conditions, CT can abiotically (through abiotic hydrolysis) or anaerobic co-metabolically (ANCM) degrade to chloroform, dichloromethane (DCM, or methylene chloride), carbon disulfide, and carbon dioxide, as shown in **Figure 2-10**. The product distribution and rate of reaction in a given system depend on several factors, including the presence of organometallic cofactors to facilitate the co-metabolism, and reducing conditions.

Under aerobic conditions, chloroform can be co-metabolically transformed via ACM to carbon dioxide (**Figure 2-10**). Under anaerobic conditions, it can undergo ANCM by methanogenic, sulfate-reducing, fermenting, and acetogenic bacteria, producing DCM, chloromethane, and carbon dioxide. Chloroform can also undergo ANDM to produce DCM. As with CT degradation, the products of chloroform depend on reducing conditions and presence of organometallic cofactors that facilitate co-metabolism.

Biotic degradation of DCM and chloromethane to innocuous end products in groundwater is well established in peer-reviewed literature and is shown to occur under both aerobic and anaerobic conditions (**Figure 2-10**). DCM can undergo ADM and ANDM (e.g., fermentation) to produce carbon dioxide and water or formate and acetic acid. Additionally, methane can be generated from ANDM of DCM and ANCM of CM. CM also can undergo abiotic hydrolysis.

3.0 FIELD IMPLEMENTATION ACTIVITIES

The following sections discuss the field preparation, mobilization, groundwater RA injections, well installation, performance monitoring activities, deviations from the work plan, data usability and validation, and investigation-derived waste (IDW) activities.

3.1 Preparatory, Mobilization, and Field Implementation Activities

The following sections present the preparatory, mobilization, and field implementation activities.

3.1.1 Preparatory, QC, and Health and Safety Meetings and Reporting

A preparatory meeting with the Site Superintendent, Caretaker Site Officer (CSO), Resident Officer in Charge of Construction (ROICC), and Remedial Project Manager (RPM) was conducted to review RA areas on April 16, 2019. Existing site utility drawings were reviewed, and a site walk was conducted. A daily status report was transmitted via email to the CSO, ROICC, and RPM by the following day, summarizing field activities. Weekly construction quality control (CQC) meetings were conducted between April 30 and December 3, 2019. During the meetings, site-specific activities and tasks required to complete the RA or performance monitoring were discussed. The weekly CQC meeting minutes are presented in **Appendix C**. Photodocumentation of field activities is provided in **Appendix D**.

Daily tailgate safety meetings were held before starting fieldwork. All field staff, including subcontractors attended these meetings led by the Site Safety and Health Officer and all personnel signed a tailgate safety meeting form. Any subcontractor, agency, or Navy personnel that visited the site were required to review and sign the tailgate safety form to acknowledge awareness of potential site hazards prior to entering a work area. There were no lost-time injuries or incidents during the execution of this project.

3.1.2 Permitting and Notifications

Per Section 121(e) of CERCLA 1980 (CERCLA, 42 United States Code, Section 9621[e]), as amended, no federal, state, or local permits were required for the portion of any removal or remedial action conducted entirely on-site. ECC-Insight obtained all necessary authorization from the HPNS CSO, ROICC and Navy RPM for performing the RA at Parcel C. Prior to field activities, ECC-Insight notified the Navy RPM, CSO, and appropriate HPNS security personnel about the nature of the anticipated work. Although formal permits were not required for all activities, substantive compliance with applicable permit requirements were met. For the San Francisco Water, Power, Sewer-Public Utilities Commission (PUC), a batch discharge permit was approved and is further described in **Section 3.6** and presented in **Appendix E**.

3.1.3 Utility Survey and Clearance

Prior to intrusive activities (e.g., drilling or injection), a geophysical survey was conducted before each field event by Ground Penetrating Radar Systems LLC (GPRS). GPRS performed the geophysical survey using ground penetrating radar, electromagnetic terrain conductivity, and employed radio frequency utility locating tools to identify the presence of both metallic and nonmetallic subsurface features. Subsurface utilities were marked on the ground surface and thus avoided during the field investigation activities. In addition, Underground Service Alert North 811 was contacted prior to intrusive activities to identify underground utilities.

3.1.4 Environmental Controls

Environmental Controls were implemented on this project in accordance with the Environmental Protection Plan (EPP), Appendix C of the RAWP (ECC-Insight and CDM Smith 2017) which included fugitive dust control, air monitoring, noise monitoring, and stormwater protection.

3.1.4.1 Dust Control

Dust control measures were implemented beginning with site mobilization and continuing during all phases of the construction activities. Work areas were kept free of debris, and all dirt and soil were cleaned from the work areas at the end of daily activities. Ambient dust was monitored during all intrusive activities per the EPP, Appendix C of the RAWP (ECC-Insight and CDM Smith 2017). In accordance with the Dust Control Plan as part of the EPP, all necessary precautions were taken to minimize the exposure of nuisance and fugitive dust to employees, the public, and surrounding buildings. Fugitive dust control measures included:

- Vehicular traffic was restricted to 15 miles per hour (mph) within the construction site and 5 mph in work areas.
- Trucks followed the designated truck route for HPNS.
- Trucks were equipped with tarping systems to cover loads during transport.

3.1.4.1 Air Monitoring

Although no excavation activities were conducted, prior to start of any intrusive activities, air monitoring stations were set up upwind and downwind of the field activities. All air monitoring was also conducted in accordance with the Accident Prevention Plan (APP) (ECC-Insight and CDM Smith 2016). Air monitoring for dust was conducted and particulates did not exceed threshold values during the project.

3.1.4.2 Noise Control

Since work around heavy equipment has the potential for excessive noise, a decibel noise meter was used to monitor noise levels during heavy equipment operation. In accordance with the APP (ECC-Insight and CDM Smith 2016), all personnel were required to wear hearing protection around heavy equipment.

3.1.4.3 Stormwater and Erosion Control

All stormwater and erosion control measures were conducted in accordance with the EPP, Appendix C of the RAWP (ECC-Insight and CDM Smith 2017). Prior to beginning of all field activities, inspections of nearby stormwater, outlets and drains were conducted to ensure they were protected. Best management practices (BMPs) included ensuring sand bags or fiber rolls were in place to contain potential runoffs. BMPs surrounding waterways were checked and monitored during rain events, to validate the effectiveness of the BMP deployed and repaired as needed.

3.1.5 Temporary Facilities and Construction Control

Temporary facilities and construction control procedures were implemented for this project. A temporary office trailer was established throughout the period of construction to store project documents, hold project meetings, and store and charge instruments. Sanitary facilities were provided and staged adjacent to the work areas. Barricades and delineators were provided as needed to prevent unauthorized personnel from entering the work area. Storage for tools and light equipment were established within the work zone.

Temporary services were coordinated with the CSO representative prior to work activities. Safety was managed, including monitoring of vehicular and pedestrian traffic and public safety, as needed. Staging

areas for drilling and injection equipment, amendment and waste storage, and equipment decontamination were coordinated with the CSO and ROICC.

3.1.6 Surveying

A California-licensed land surveyor conducted land surveying activities at all boring and monitoring well locations. The field investigation locations were surveyed to within a 0.01-foot horizontal and vertical accuracy using the State Plane Coordinate System. The horizontal coordinates were established based on North American Datum of 1983. Vertical coordinates were surveyed to the North American Vertical Datum of 1988 and elevations were reported as feet amsl (**Appendix F**). The geospatial data for borings and monitoring wells were uploaded to the Naval Installation Restoration Information Solution in accordance with the Data Management Plan (ECC-Insight and CDM Smith 2017).

3.2 Groundwater Remedial Action Injection Activities

Between April 25 and May 31, 2019, hydraulic fracturing was performed to facilitate emplacement of ZVI, sodium lactate (WilclearPlus®), and emulsified vegetable oil (LactOil®) into the target treatment zones at RU-C2-3 and RU-C1-1 (**Table 3-1; Figures 3-1 and 3-2**). For RU-C1-1 and RU-C2-3 combined, 46 boreholes were subject to hydraulic fracturing with a total of 205 fracture depths (11 fracture depths at RU-C1-1 and 194 fracture depths at RU-C2-3; **Tables 3-1 through 3-3**). The vertical depths targeted for hydraulic fracturing at RU-C1-1 and RU-C2-3 ranged between approximately 7 to 15 feet bgs and 12 to 29 feet bgs, respectively. In addition to the hydraulic fracturing, tiltmeter monitoring was concurrently performed at select boreholes at RU-C1-1 and RU-C2-3 to verify amendment distribution (**Tables 3-2 and 3-3**). Approximately 3 months following the hydraulic fracturing, bioaugmentation was performed at select monitoring wells at RU-C2-3 to facilitate biotic dechlorination of COCs. Details pertinent to the hydraulic fracturing, tiltmeter monitoring, and bioaugmentation are provided in the following subsections. Groundwater injection implementation reports are provided in **Appendix G**.

3.2.1 Hydraulic Fracturing

Hydraulic fracturing was performed by Geo Tactical Remediation Ltd., under the supervision and direction of ECC-Insight and CDM Smith, using an EF9300 skid-mounted mixing and pumping unit using a bottom-up emplacement methodology in open boreholes (**Appendix H**). An inflatable straddle packer assembly, consisting of upper and a lower sealing elements connected to one another by a stainless steel interval with two perforations was used to isolate the depth-discrete vertical interval of interest inside an open borehole drilled to approximately 8 feet below the deepest target treatment interval. A roto-sonic (sonic) drill rig was used to drill the 4¼-inch diameter open boreholes in advance of the hydraulic fracturing work. To prevent subsurface sloughing, 4-inch inner diameter polyvinyl chloride (PVC) sections with a threaded bottom cap were lowered into each open borehole upon completion of the drilling work. A top-down, single packer emplacement methodology was used at INJ-1 at RU-C1-1 because significant sloughing was encountered, rendering the bottom-up, straddle-packer emplacement methodology infeasible.

Prior to hydraulic fracturing, a hoist truck was used to emplace the straddle packer assembly. Subsequently, the packer assembly was pressure- and leak-checked aboveground. Following these checks, the packer assembly was lowered to the deepest vertical target treatment interval of interest using the hoist truck then inflated with water using a pressure washer to create an isolated zone to be subject to hydraulic fracturing. Steel pipes were used to connect the downhole packer assembly with the aboveground wellhead assembly, whereas pressure-rated hoses were used to connect the EF9300 skid with the wellhead assembly. Once the packer assembly was lowered to the target treatment interval and inflated properly, the appropriate amount of ZVI, WilclearPlus®, and LactOil® were batch mixed on the EF9300 with potable water and Geo Tactical

Remediation Ltd.'s proprietary high-viscosity fluid system. The high-viscosity fluid system was designed to allow maximum suspension of the ZVI in the fracturing fluid (**Appendix H**).

Hydraulic fracturing was performed at 3 boreholes at RU-C1-1 and 43 boreholes at RU-C2-3, respectively (**Table 3-1; Figures 3-1 and 3-2**). Three depth-discrete intervals ranging between approximately 7 and 15 feet bgs were subject to hydraulic fracturing at each of the three injection locations at RU-C1-1. Four to five depth-discrete intervals ranging between approximately 12 and 29 feet bgs were targeted for hydraulic fracturing at each of the 43 injection locations at RU-C2-3.

Details pertinent to the target injection design at RU-C1-1 and RU-C2-3 are provided in **Tables 3-1 through 3-3**. A ZVI mass loading of approximately 0.4 percent by weight (wt%) of ZVI per soil mass was targeted for the target treatment volume at RU-C1-1 (**Table 3-2**). A low and a high ZVI mass loading were targeted based on COC concentrations at RU-C2-3. For RU-C2-3, a low ZVI mass loading of 0.25 wt% was targeted at 23 boreholes, and a high ZVI mass loading of approximately 0.4 wt% was targeted at 20 boreholes (**Table 3-3**). A summary of the hydraulic fracturing at both RU-C1-1 and RU-C2-3, which includes the amount of ZVI, WilclearPlus®, and LactOil® added at each injection location, is presented in **Tables 3-1 through 3-3**. The target injection mass/volume for ZVI was met at approximately 101%.

3.2.2 Tiltmeter Monitoring

Concurrent with the hydraulic fracturing described in **Section 3.2.1**, tiltmeter mapping was performed at one injection location at RU-C1-1 and 15 injection locations at RU-C2-3 to evaluate the distribution of amendment emplaced in the subsurface (**Tables 3-2 and 3-3; Figures 3-1 and 3-2; Appendix H**). Prior to hydraulic fracturing activities at each injection location, biaxial ES model 700 tiltmeter sensors were placed in two concentric circular arrays (inner and outer) around the borehole location to monitor the micromovements in the ground surface in response to each pumping event. Tiltmeters were set on prepared locations and leveled to read a tilt angle of approximately zero degrees. During each pumping event, tilt signal data were collected and stored in the memory modules of dataloggers at a collection frequency of one (1) tilt data signal every 10 seconds. Upon the completion of pumping at each interval, the tiltmeter sensors were leveled again as required in preparation for the next pumping event. This process was repeated until fracture initiation was completed at all depth-discrete intervals of interest within an injection borehole.

Tiltmeter data were analyzed using inverse parameter modeling to determine the orientation and geometry (modeled as planar rectangular features) of each fracture initiated. Orientation was defined by azimuth direction and angle of ascent from horizontal (measured in degrees), and geometry is defined by length, width, and thickness. Since not all the locations had tiltmeter monitoring performed, dimensions obtained from the locations (e.g., fracture lengths, widths, and azimuths) were used to obtain approximate dimensions for all fractures based on the interval of the fracture injection, with Fracture Interval 1 as the deepest interval. Calculated averages of these dimensions were used to estimate coverage of the fracture networks for all borings within the target treatment volumes, as discussed in **Sections 4.1.1 and 4.2.1**.

3.2.3 Monitoring Well Redevelopment

After emplacement of amendment via hydraulic fracturing, approximately 1 liter of groundwater was collected with a bailer from each of the monitoring wells in the injection area. The groundwater samples settled for 1 to 2 days. If significant ZVI was visually noted in the sample after settling, the well from which the sample was obtained was redeveloped to prevent potential clogging of the well screens with ZVI.

Well redevelopment was completed between May 29 and 31, 2019, at IR28MW941F and IR28MW300F and consisted of a combination of mechanical surging, bailing, and pumping. Wells were surged a minimum of 20 times across the entire length of the screen. A downhole Monsoon pump was used to pump the wells

at flow rates ranging from 0.18 to 0.38 gallons per minute, and water quality parameters were measured using a Horiba U-52 water quality meter. During pumping, water was observed to be dark grey to black and often viscous because of the presence of ZVI and guar. Wells were pumped until the presence of ZVI and guar were negligible in the purge water and water quality parameters stabilized as described in **Section 3.3.1**. Well redevelopment logs are provided in **Appendix I**.

3.2.4 Bioaugmentation

Approximately 2 weeks prior to the start of the bioaugmentation work, 500 gallons of anoxic chase water was prepared by adding 3% WilclearPlus® (by volume) to potable water. The anoxic water was prepared in 275-gallon totes, which were left to incubate for approximately 2 weeks to allow for the water to turn anaerobic. Dissolved oxygen (DO) and oxidation-reduction potential (ORP) were tested using a pre-calibrated multiparameter water quality meter following the incubation period; very low DO (0.1 mg/L) and ORP (–250 millivolt) were observed. Bioaugmentation was performed at RU-C2-3 on August 27 and August 28, 2019. Monitoring wells located within the footprint of the RU-C2-3 plume that were subject to bioaugmentation included: IR28MW300F, IR28MW941F, IR28MW939F, and IR28MW190F. Compression fittings were used to allow for bioaugmentation and injection as shown in **Figure 3-3**.

Prior to bioaugmentation, argon gas was used to flush the headspace inside each monitoring well of interest. Argon gas flushing was performed for approximately 5 minutes to achieve a headspace oxygen concentration of below 1% by volume. Following the argon gas flushing, approximately 12.5 liters of the concentrated KB-1™ (SiREM®) culture were injected into each of the wells. Nitrogen gas was used to pressurize the stainless steel keg containing the culture and to facilitate the transfer of the culture into subsurface. Following the injection of the culture, between 100 and 150 gallons of the prepared anoxic water were injected into each of the four monitoring wells using a submersible pump to further distribute the culture into the surrounding formation. The amount of culture and anoxic chase water added to each of the four monitoring wells is presented in **Table 3-4**.

3.3 Performance Monitoring Activities

Performance monitoring activities involved the installation of four new monitoring wells, the sampling of all performance monitoring wells, synoptic water level measurements, as discussed in the following subsections. Performance monitoring wells included the following (**Table 3-6**):

- RU-C1-1: IR28MW338A and IR28MW938A
- RU-C2-3: IR28MW190F, IR28MW300F, IR28MW939F, IR28MW940F, and IR28MW941F

3.3.1 Remedial Action Monitoring Well Installation and Development

Per the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**), four new monitoring wells were installed in December 2018 (IR28MW938A, IR28MW939F, IR28MW940F, and IR28MW941F) to support the performance monitoring evaluation at RU-C1-1 and RU-C2-3. In RU-C1-1, monitoring well IR28MW938A was installed east of the plume (**Table 3-5; Figure 3-1**). In RU-C2-3, monitoring well IR28MW939F was installed inside Building 258, monitoring well IR28MW940F was installed inside Building 251, and monitoring well IR28MW941F was installed between Buildings 258 and 251 (**Table 3-5; Figure 3-2**). Monitoring well construction logs are presented in **Appendix B**.

The boreholes for the new monitoring wells were advanced using sonic drilling methods in accordance with the Sampling and Analysis Plan (SAP) (*Appendix A* of the RAWP [ECC-Insight and CDM Smith 2017]). Boreholes were logged per the Unified Soil Classification System (USCS) using the Visual-Manual Method (American Society for Testing and Materials [ASTM] Standard D2488) under the supervision of a

professional geologist (**Appendix B**). The monitoring wells were constructed with a 2-inch-diameter, schedule 40 PVC well casing with flush-threaded joints. All well screens consisted of 10 feet of 2-inch-diameter, schedule 40 PVC, 0.010 inches machine slotted pipe, except for IR28MW938A, which consisted of 5 feet of screen (**Table 3-5; Appendix B**).

Each installed monitoring well was developed to ensure purge water was representative of the formation. Development was performed in accordance with the SAP (*Appendix A* of the RAWP [ECC-Insight and CDM Smith 2017]). Well development consisted of a combination of mechanical surging, bailing, and pumping. Wells were surged a minimum of 20 times across the entire length of the screen. A downhole Grundfos pump (or equivalent) was used to pump the wells at flow rates ranging from 0.16 to 0.18 gallons per minute, and water quality parameters were measured using a YSI 6820 water quality meter (or equivalent). Wells were pumped until water quality parameters, including DO, ORP, turbidity, temperature, and conductivity, had stabilized. Well development logs are provided in **Appendix I**. Purge water was containerized and IDW was managed as described in **Section 3.6**.

3.3.2 B-Aquifer Monitoring Well Installation and Development

As part of the response to the BCT comments in review of the characterization results for RU-C2-1 as presented in the RAWPA (**Appendix A**), two new monitoring wells were constructed in the B-aquifer east and downgradient of the RU-C2-1 plume. Monitoring wells RUC21MW15B and RUC2MW16B were installed in December 2018 and May 2019, respectively. Monitoring well construction logs are presented in **Appendix B (B-3)** and analytical results and a location map are presented in **Appendix J (J-2 and Figure J-2)**.

The boreholes for the new monitoring wells in the B-aquifer were advanced using sonic drilling methods in accordance with the SAP (*Appendix A* of the RAWP [ECC-Insight and CDM Smith 2017]). Boreholes were logged per the USCS using the Visual-Manual Method (ASTM Standard D2488) under the supervision of a professional geologist. The monitoring wells were constructed with 2-inch-diameter, schedule 40 PVC well casing with flush-threaded joints. Both well screens consisted of 10 feet of 2-inch-diameter, schedule 40 PVC, 0.010 inches machine slotted pipe and were set from 45 to 55 feet bgs (**Table 3-5; Appendix B**).

Both monitoring wells were developed to ensure purge water was representative of the formation. Development was performed as specified in the SAP (*Appendix A* of the RAWP [ECC-Insight and CDM Smith 2017]). Well development was performed as described in **Section 3.3.1**. Well development logs are provided in **Appendix I**. Purge water was containerized and IDW was managed as described in **Section 3.6**.

3.3.3 Groundwater Sampling

Groundwater samples were collected from all performance monitoring wells during baseline and post-RA events. Baseline groundwater sampling was performed for all performance monitoring wells prior to the RA. In pre-existing monitoring wells, baseline data were collected in November 2017 and presented in the RAWPA (ECC-Insight and CDM Smith 2019a; **Appendix A**). In newly installed monitoring wells, baseline sampling was performed shortly after well development in December 2018. All seven RU-C1-1 and RU-C2-3 performance monitoring wells were sampled in June 2019, August 2019, and December 2019 during the 1-month, 3-month, and 6-month post-RA sampling events. The groundwater sample summary, including analyzed parameters and monitoring schedule, is presented in **Table 3-6**. All analytical results are tabulated in **Appendix J**. Laboratory reports are provided in **Appendix M**.

Sampling procedures were performed per standard operating procedures (SOPs) outlined in the RAWP (ECC-Insight and CDM Smith 2017). Water quality parameters (i.e., field parameters), including temperature, pH, DO, ORP, turbidity, conductivity, and ferrous iron, were measured during well purging prior to sampling. Water quality parameters were measured using a Horiba U-52 with a LaMotte 2020WE Turbidimeter or a YSI 6820 with an optical DO sensor, and ferrous iron was measured with a HACH 8146 test kit. Groundwater samples were collected following the stabilization of water quality parameters. The field documentation for all four sampling events is presented in **Appendix I**. Purge water was containerized and IDW was managed as described in **Section 3.6**.

3.3.4 Water Level Measurements

During each baseline and post-RA monitoring event, a monitoring well water level was measured prior to sampling. Water level elevations for each of the four monitoring events are included in **Table 3-5**.

3.4 Deviations from the Work Plan

The following deviations from the RAWP and RAWPA were made because of field conditions and technical considerations:

1. Bioaugmentation was performed at the monitoring wells approximately 3 months following the initial hydraulic fracturing and amendment emplacement. A high pH enzyme breaker was used as part of the hydraulic fracturing process, which in combination with the high solid content would have been detrimental to the microbial viability and proliferation in the subsurface if emplaced simultaneously with the ZVI/ISB amendments. The 3 months post-hydraulic fracturing allowed for development of highly reducing conditions conducive to bioaugmentation. Bioaugmentation was not performed at RU-C1-1 because ZVI injections were conducted to abiotically treat COCs, and COCs in monitoring wells within the treatment area were below RGs.
2. As shown in **Table 3-3**, at many of the injection boreholes at RU-C2-3, the number of depth-discrete intervals subject to hydraulic fracturing was reduced from five to four at some locations to decrease the likelihood of fluid surfacing from the shallowest treatment interval. Quantity (volume and mass) of amendment injected within each borehole was adjusted (i.e., increased) accordingly between the fractures to achieve the required target in situ dose of amendments. The target amendment injection quantities were achieved at both RUs in accordance with the RAWPA (**Appendix A**).
3. Two injection locations were originally targeted to address groundwater contamination near monitoring well IR28MW940F. However, because of heaving sands and borehole collapse encountered in that area, only one ZVI/ISB injection location was successfully completed at this location (Low-22), despite multiple attempts (**Figure 3-2**). After several attempts to advance a second location (Low-23) in the IR28MW940F vicinity, Low-23 was moved to the west of Building 251. The heaving sand leading to borehole collapse can be attributed to the F-WBZ dipping steeply to the east, which exposes shallow A-aquifer material (clayey sand) at approximately 15 to 20 feet bgs beneath Building 251 (**Figure 2-5**).
4. Additional LactOil® and WilclearPlus® were added to the ZVI injection at RU-C1-1.
5. Water level measurements were collected at each performance monitoring well prior to sampling. For RU-C1-1, only two monitoring wells were sampled; therefore, groundwater gradient magnitude and direction were not evaluated for individual sampling events – instead the baseline

June 2018 groundwater gradient was used to assess the magnitude and direction of flow in RU-C1-1.

3.5 Data Usability and Assessment Summary

Analytical data collected for this project were reviewed by a third-party data validation company, Laboratory Data Consultants (LDC), according to the requirements specified in the RAWP (ECC-Insight and CDM Smith 2017). Data was validated according to the U.S. EPA National Functional Guidelines for Inorganic Data Review, EPA 540-R-2017-001 (U.S. EPA 2017), U.S. EPA National Functional Guidelines for Organic Data Review, EPA 540-R-2017-002 (U.S. EPA 2017), NAVFAC Southwest Environmental Work Instruction (EWI) Number 1 (NAVFAC Southwest 2001), and the United States Department of Defense (DoD) Quality Systems Manual for Environmental Laboratories, Version 5.1 (DoD Environmental Data Quality Workgroup 2017). The findings of the data validation process are provided in **Appendix N** and were used to document the quality of the analytical data used for project decisions. Based on the data validation, there were no significant systematic problems identified with the analytical method performance.

3.5.1 Quality Assurance Objectives

Quality assurance (QA) objectives for analytical data are expressed in terms of precision, accuracy, representativeness, comparability, completeness, and sensitivity (PARCCS). The QA objectives provide a mechanism for ongoing control in the process of evaluating and measuring data quality throughout the project.

A review of the data was completed in order to determine if data quality meets the project objectives established in the seven-step Data Quality Objective (DQO) process and documented in the SAP (ECC-Insight and CDM Smith 2017). In general, the following data measurement objectives were considered:

- Verification that the analytical procedures and the reported results were consistent with the methods and requested practical quantitation limit (PQL) goals.
- Evaluation of data as compared to PARCCS parameter criteria specified in the SAP, through assessments of laboratory QC and field QC sample results
- Identification of specific sample-handling issues or other project-specific issues and an assessment of the impact on the PARCCS parameter measurement performance objectives of representativeness and comparability
- Qualification of data in accordance with
 - U.S. EPA SW846 Third Edition, Test Methods for Evaluating Solid Waste, update 1, July 1992; update IIA, August 1993; update II, September 1994; update IIB, January 1995; update III, December 1996; update IIIA, April 1998; IIIB, November 2004; update IV, February 2007; update V, July 2014
 - U.S. Department of Defense Quality Systems Manual for Environmental Laboratories, Version 5.0, July 2013; and Version 5.1, October 2017

The data validation provides a system for the evaluation and documentation of factors that may affect the project data and determines whether the data are of sufficient quality to support their intended use.

3.5.2 Summary of Field and Laboratory QA Activities

All sampling activities were performed in accordance with the SAP (ECC-Insight and CDM Smith 2017). The RA and performance monitoring activities included the collection of 125 groundwater samples. In addition, QC and IDW samples were collected to support data validation and IDW waste profiling. Samples were collected and shipped to Enthalpy Analytical, EMAX Laboratories (a subset of volatile organic analyses), and Microbial Insights (bacteriological census). The SAP defined the procedures to be followed and the data quality requirements for the field program.

3.5.3 Field QC

Field QC samples were collected at the frequencies described in the SAP to determine the quality of the field data. Temperature blanks were included with each shipment of samples. Field equipment was calibrated daily per the SOPs in the SAP. Analytical results for QC samples are included in **Appendix J**.

Field QC sample objectives were accomplished using appropriate sampling techniques and collection of field duplicates, equipment rinsate blanks, field blanks, and trip blanks. Analytical QA/QC was assessed by laboratory QC checks, preparatory and method blanks, surrogate spikes, adherence to holding times, laboratory control samples (LCSs), matrix spike/matrix spike duplicates (MS/MSDs), internal standards, internal and continuing calibration recoveries, and sample custody tracking.

3.5.4 Chemical Laboratory Methods

Groundwater and soil samples were analyzed for the following analytical methods per the SAP (ECC-Insight and CDM Smith 2017):

Analyses - Analytical Method	Groundwater	Soil
VOCs - EPA Method 8260B	X	X
TOC - EPA 415.1/Standard Method (SM) 5310C	X	
Dissolved Gases - RSK-175	X	
Alkalinity – EPA 3101.1/SM2320B	X	
Anions – EPA 300.0		
Metals including Mercury - EPA Method 6020/7470/7471A	X	X
DHC and functional genes – qPCR	X	
TPH diesel and motor oil range organics and gasoline range organics - EPA Method 8015B		X
PCBs - EPA Method 8082		X

3.5.5 Data Validation Procedures

Data were validated by LDC, an independent data validation firm; complete data validation reports are included in **Appendix N**. The data validation was performed in accordance with NAVFAC SW EWI Number 1, Chemical Data Validation, dated November 28, 2001. EWI No. 1 is compiled from the EPA Contract Laboratory Program National Functional Guidelines (NFGs) for Inorganic and Organic Review (EPA 2017).

HPNS is designated by the EPA as a NPL site which indicates a data validation strategy comprised of 80 percent Level III (i.e., Stage 2b) data and 20 percent Level IV (i.e., Stage 3) data, as indicated in EWI No.1. Level III data validation included review of: chains-of-custody and cooler temperature upon laboratory receipt, sample results, sample preparation and analysis dates, holding times, laboratory and field QC blanks, surrogate recoveries, LCS/LCSD and MS/MSD summaries, initial and continuing calibration and internal standard summaries, sample preservation, and laboratory logs. In addition to Stage 2b review elements, Stage 3 validation included review and assessment of analytical raw data.

Where specific guidance was not available, the data were evaluated in a conservative manner consistent with industry standards using professional experience and judgment. The analyses were validated using the following documents, as applicable to each method:

- EPA, Contract Laboratory Program NFGs for Superfund Organic Methods Data Review, January 2017
- EPA, Contract Laboratory Program NFGs for Inorganic Data Review, January 2017
- EPA SW 846, Third Edition, Test Methods for Evaluating Solid Waste
- NAVFAC SW EWI No.1, Chemical Data Validation, November 28, 2001.

The data validation narratives (**Appendix N**) indicate that the sample analyses met the QC criteria cited in the methods and appropriate validation guidance documents and that 80% of field samples were subjected to Stage 2b data validation and the remaining 20% were subjected to Stage 3 data validation. Results associated with QC outliers were appropriately qualified by LDC. All analyses were conducted in accordance with the specifications of each analytical method. No field sample results were rejected as a result of data validation. Laboratory analytical results are provided in **Appendix M**.

3.6 Investigation-Derived Waste

IDW was handled per the Waste Management Plan (WMP) (*Appendix D* of the RAWP, ECC-Insight and CDM Smith 2017). State and federal hazardous waste regulations were followed during IDW generation, characterization, treatment, and management per Title 22 CCR Sections 66261, 66262, 66264, 66265 and 40 CFR Parts 260, 261, 262, 264 265, 268. Transportation of hazardous and nonhazardous waste is regulated by 22 CCR Section 66262 and United States Department of Transportation requirements. IDW generated during the field investigation included soil cuttings, purged groundwater, well development, decontamination fluid, and PPE.

All solid wastes were stored in properly labeled 55-gallon drums and 20-cubic-yard covered roll-off bins, with waste generation date, waste origin, contractor's name, and phone number. Additionally, drums were labeled as pending characterization and profiling for final disposal. Weekly inspections of all drums were performed to ensure wastes were stored in compliance with the WMP. Liquid waste was temporarily stored in drums and transported to an on-site 2,500-gallon capacity polyethylene tank, staged northwest and outside of Building 211. All drums were stored within secondary containment in areas delineated with barricades and caution tape at the following staging areas:

- Solid waste generated from field activities performed at RU-C1-1 were stored at Building 251.
- Solid waste generated from field activities performed at RU-C2-3 were stored at Building 258.

The contents of all soil drums were consolidated into three 20-cubic-yard covered roll-off bins with liners. Following consolidation, representative samples were collected from each bin and, per receiving landfill requirements, were submitted to Enthalpy Laboratories for the following chemical analyses:

- VOCs (EPA Method 8260B)
- Oil and Grease (EPA Method 1664A)
- PCBs (EPA Method 8082)
- TPH-Diesel (EPA Method 8015M)
- TPH-Gas (EPA Method 8015M)
- CAM-17 Metals (EPA Method 6010B, TCLP and WET Leachate)

The laboratory analytical results were profiled, and manifests were prepared and submitted to Potrero Hills Landfill in Suisun, California. Following approval on September 18 and 19, 2019, all three bins were transported to the Potrero Hills Landfill for recycling as follows (**Appendix E**):

1. Manifest No. H-19223, Bin No. 6696, 14 cubic yards (9/18/2019)
2. Manifest No. H-19224, Bin No. 6469, 14 cubic yards (9/19/2019)
3. Manifest No. H-19225, Bin No. 6152, 16 cubic yards (9/18/2019)

All three bins and trucks were radiologically screened through a Rad portal operated by the Navy's Basewide radiological contractor (APTIM) prior to being transported off site.

The polyethylene tank contained approximately 2,400 gallons of liquid waste. A batch discharge permit to discharge the contents to the sanitary sewer, was applied for and approved by the PUC. The PUC processed the batch discharge application per San Francisco Public Works Code Article 4.1, Section 123 {Sewer Use Ordinance}. As part of the application process samples were collected from the tank's content and analyzed for the following parameters:

- VOCs (EPA Method 8260B)
- SVOCs (EPA Method 8270C)
- TPHd/mo (EPA Method 8015B)
- TPHg (EPA Method 8015B)
- PCBs (EPA Method 8082)
- Ignitability/Flashpoint (ASTM Method D93)
- Title 22 Metals plus Fe/Mn (EPA Method 6020/7470A)
- Oil and Grease (EPA Method 1664A)
- TSS (Method SM2540-D)
- Chloride (EPA Method 300/4500-C)
- Dissolve Sulfide (Method SM4500S2-D)
- Mercury (EPA Method 7470)
- Phenolic Compounds (EPA Method 420.1)

- COD (Method SM5220D)
- Total Cyanides (Method SM4500CN-C, E)
- Pesticides (EPA Method 8081A)
- Herbicides (EPA Method 8151)

Based on the analytical results, the PUC approved the batch wastewater discharge permit (Permit No. 20-01968) on January 31, 2020. On February 6, 2020, the contents of the polyethylene tank (approximately 2,400 gallons) were discharged into an approved sanitary sewer location at an on-site manhole at HPNS along Crisp Road. The discharge was in compliance with Article 4.1 of the City's Department of Public Works' Order No. 1581170.

General refuse (such as packaging materials, shipping boxes, and pieces of broken/unused well screens or casings) were managed as nonhazardous waste and transferred to an on-site, 30-yard-capacity industrial dumpster. Those contents were disposed of at the local municipal landfill after the dumpster and truck were screened through the Rad portal operated by the Basewide radiological contractor before leaving HPNS.

Waste manifests and PUC permits are included in **Appendix E**.

3.7 Site Restoration and Demobilization

All injection point locations were decommissioned following injections, and the surface was restored to match existing conditions. For injection points, all equipment was removed prior to tremie-grouting each borehole. Each borehole was tremie-grouted with a cement-bentonite mixture from the bottom of the borehole to ground surface. Surface completions were grouted to the ground surface. For locations outside buildings in paved areas, surface completions complied with the durable cover requirements.

Demobilization consisted of decontamination and removal of equipment used to conduct the remediation and the collection and disposal of contaminated material, including decontamination water and disposable equipment where decontamination was inappropriate. Waste transport and manifesting was coordinated with the CSO representative. Demobilization related to the remediation activities was completed on May 31, 2019. Performance groundwater site restoration activities were completed in December 2019.

4.0 REMEDIAL ACTION PERFORMANCE MONITORING RESULTS

This section describes the RU-C1-1 and RU-C2-3 performance monitoring results, including baseline and post-RA monitoring at 1-month, 3-month, and 6-month sampling events. Performance monitoring includes collecting data to evaluate amendment distribution, geochemical and microbial parameters supporting COC degradation, and COC concentrations and trends. Tiltmetering results are presented in **Tables 4-1** through **4-3**. Baseline and post-RA results for COCs, geochemical parameters, and microbial parameters are presented in **Tables 4-4** and **4-5**. Metals results are summarized in **Table 4-6**. Comprehensive data for the baseline and the three post-RA monitoring events are tabulated in **Appendix J**. Trend charts for COCs, geochemical parameters, and microbial parameters are presented in **Appendix K**.

Amendment delivery and distribution is presented for the injection activities for RU-C1-1 and RU-C2-3. Multiple lines of evidence were used to evaluate the lateral and vertical distribution of amendment following injections. Field observations of amendment in monitoring wells, advanced tiltmeter monitoring, and carbon and geochemical analysis were all used as lines of evidence for amendment delivery and distribution. Additionally, expansion of the treatment zone is evidenced by assessment of changes in geochemical conditions, COC profiles, and microbial populations over time at performance monitoring wells as impacts migrate downgradient and expand the volume impacted by the injections over time.

4.1 RU-C1-1 Performance Monitoring

The COCs exceeding RGs in the RU-C1-1 plume are PCE, TCE, VC, and benzene. **Table 4-4** presents the RU-C1-1 RA performance monitoring data and geochemistry for wells IR28MW338A and IR28MW938A. As discussed in **Section 3.2**, hydraulic fracturing was successful in emplacing 6,871 pounds of ZVI, and 45 gallons of LactOil®/ or WilclearPlus® into the three fracture borings (INJ-1, -2 and -3) as shown in **Figure 4-1**. The following sections describe results and evaluation of amendment delivery, geochemical response, and COC treatment for RU-C1-1. Trend charts for COCs, geochemical parameters, and microbial parameters are presented in **Appendix K**.

4.1.1 Amendment Delivery and Distribution

The following discussion focuses on the initial evaluation of amendment delivery and distribution based on field observations made during hydraulic fracturing, two-dimensional (2-D) and 3-D visualization of the fracture network generated by tiltmeter monitoring and analysis, and changes in TOC and ferrous iron at performance monitoring wells at RU-C1-1, following the initial amendment emplacement.

Field Observations

As shown in **Figure 4-1**, 3 boreholes were advanced at RU-C1-1, and an amendment slurry comprised of ZVI, LactOil®, and WilclearPlus® was emplaced in the subsurface as discussed in **Section 3.2**. **Tables 3-1** and **3-2** summarize the volumes of amendment injected into each borehole at each fracture location. In general, all the volume was injected successfully with only a minor amount of amendment surfacing observed at INJ-1 during hydraulic fracturing. Surfacing was not observed at INJ-2 or INJ-3 fracture borings. Grab groundwater samples were collected from monitoring well IR28MW938A, which indicated some observation of amendments after injections (**Figure 4-2**).

Tiltmeter

Tiltmeter monitoring is discussed in **Section 3.2**. Tiltmeter geophysics was used to evaluate the distribution of amendment emplaced by fracturing at INJ-3 in RU-C1-1 (**Table 4-1**). Of the three fractures evaluated for borehole INJ-3, the tiltmeter geophysics demonstrated that extents of individual fractures ranged from

17.5 to 25.8 feet in length, 7 to 20.4 feet in width, and the angle of inclination from horizontal (i.e., dip angle) was 15 to 33 degrees. This indicates the fractures had a moderately ascending (i.e., propagated upwards) orientation (**Table 4-1**).

As shown in **Figure 4-1**, fracture propagation resulted in emplacement of amendment slurry beyond the immediate area of the borehole. The fractures appear to have propagated in all directions between 10-12 feet except in the northerly direction, where propagation was less than 10 feet.

Pumping efficiency is the modeled fracture injection volume (theoretical) divided by the actual volume emplaced. A low pumping efficiency indicates most fluid “leaked” to a more permeable formation and that only a small fraction of the amendment remains in the initiated and propagated fractures. For RU-C1-1, the pumping efficiency was less than 10% at INJ-3 (**Appendix H**, Geo Tactical Remediation Ltd. 2019), which suggests most amendment went out into the formation and was not retained in the fractures. This is typical of hydraulic fracturing injection in unconsolidated materials such as the fill observed in A-aquifer at RU-C1-1.

TOC and Iron

TOC is used as a direct measure for the ISB amendments. Dissolved and ferrous iron are used as the measure for ZVI and anaerobic redox conditions that facilitate iron reduction. No notable changes in TOC concentrations were observed at the two RU-C1-1 performance monitoring wells, following the initial amendment injection via hydraulic fracturing (**Table 4-4**). Similarly, no notable changes in dissolved iron or ferrous iron concentrations were observed following the initial amendment injection (**Table 4-4**).

Collectively, these field observations, tiltmeter data, TOC, and ferrous iron measurements indicated that while the hydraulic fracturing resulted in successful emplacement of amendment with extents of 20 feet or less in most directions. This explains the lack of evidence of amendments observed in the performance monitoring wells, which are at least 22 feet from the nearest injection borehole. However, as shown in **Figure 4-1**, coverage of the amendment extended to the elevated hotspot near RUC11HPT04.

4.1.2 Groundwater Gradient and Post-RA Amendment Transport

Figure 2-8 presents the potentiometric surface based on water levels collected at RU-C1-1 in June 2018 during the pre-RA characterization. Groundwater elevations in the A-aquifer ranged from 4.35 feet amsl at well IR28MW128A to 3.32 feet amsl at well IR28MW122A in June 2018. The horizontal hydraulic gradient of the A-aquifer in RU-C1-1 is approximately 0.0004 foot/foot in the southeast direction dropping off to a gradient of 0.005 foot/foot along the margin of the Bay. Vertical gradient was calculated for two A/B aquifer well clusters (IR28MW136A/ IR28MW557B and IR28MW338A/ IR28MW399B) (Table 3-6 of **Appendix A**). Results of the analysis show a slight upward gradient between the A and B aquifers separated by the Bay Mud aquitard.

During the performance monitoring events, only two wells were sampled at RU-C1-1. Because the pre-RA characterization at RU-C1-1 included synoptic water levels at several wells, the local potentiometric surface from June 2018 was used for performance monitoring groundwater flow direction.

4.1.3 Geochemical Parameters

Overall, limited changes in redox conditions were observed in the two RU-C1-1 performance monitoring wells IR28MW338A and IR28MW938A, 6 months following the RA (**Table 4-4**). Slightly aerobic (i.e., anoxic) geochemical conditions were observed at IR28MW338A at baseline as evidenced by DO of 1.49 mg/L. DO was measured at 0.31 mg/L at IR28MW938A during baseline conditions. Following the ZVI/ISB amendment injection, DO concentrations at IR28MW338A decreased to 0.07 mg/L by December 2019 but

were at 1 mg/L at IR28MW938A. No other notable changes in geochemical parameters were observed. Methane concentrations remained similar to baseline, nitrate concentrations remained low, sulfate concentration remained relatively elevated (>40 mg/L), ferrous iron remained low, and ORP remained negative in both wells. In addition, pH remained elevated (greater than 9.5) in both wells. The relatively high pH is not ideal for biotic degradation of COCs. Collectively, geochemical parameters indicate that the redox conditions at IR28MW338A and IR28MW938A have remained anoxic.

4.1.4 Microbial Biomarkers

Bioaugmentation was not performed at RU-C1-1 because COCs were below levels that would support dechlorinating cultures, and the IR28MW338A area was previously bioaugmented (APTIM 2018). The very low concentrations of chlorinated ethenes observed at both RU-C1-1 performance monitoring wells would not support growth and activity of a dechlorinating culture. Samples were collected for *Dhc* and functional genes at the 6-month (December 2019) sampling event (**Table 4-4**), and concentrations were observed at up to 44 gene copies per milliliter at IR28MW338A but were nondetect at IR28MW938A.

4.1.5 COCs

Target COCs for treatment at RU-C1-1 include chlorinated ethenes PCE, TCE, cis-1,2-DCE, and VC. As discussed in **Section 2.7**, treatment through ZVI and ISB is intended to create conditions within a treatment volume that support a variety of biotic and abiotic COC degradation mechanisms. In addition to the geochemical and microbial biomarkers described in **Sections 4.1.3** and **4.1.4**, COC concentration trends and degradation by-products were evaluated to track performance of the treatment. Trend charts for COCs, degradation products, and geochemical parameters are presented in **Appendix K**.

Concentrations and Trends

RU-C1-1 performance monitoring wells are located approximately on the northern (IR28MW338A) and eastern (IR28MW938A) treatment boundary for the PCE plume (**Figure 4-3**). Low levels of PCE and VC were observed in the RU-C1-1 monitoring well IR28MW338A during the baseline sampling event with concentrations above RGs but below ATC (**Table 4-4**). During the post-RA monitoring period, PCE concentrations initially increased slightly to 11 µg/L but declined to 2.3 µg/L by the 6-month post-RA sampling event (December 2019). VC concentrations remained stable from 6.3 to 7.1 µg/L at IR28MW338A between the baseline and the 6-month post-RA Sampling event (**Figure 4-3**; **Appendix K**).

No COCs exceeding RGs were observed in IR28MW938A during any of the monitoring events.

Degradation Parameters

The RA approach for RU-C1-1 was to promote both abiotic (primary) and biotic (secondary) RD of PCE and its lesser chlorinated degradation products. Biotic degradation of chlorinated ethenes, such as PCE, results in the sequential dechlorination to TCE, cis- or trans-1,2-DCE, VC, ethene, and ethane (**Figure 2-9**). Abiotic beta elimination reactions convert PCE to acetylene and then to ethene and ethane (primarily as ethane). Low concentrations of TCE, cis-1,2-DCE, and trans-1,2-DCE were detected in IR28MW338A and IR28MW938A during baseline and post-RA monitoring events. While concentrations fluctuated slightly, there was no overall trend in results. VC was present at concentrations exceeding the RG in IR28MW338A during all four monitoring events. However, detection of ethene and ethane (e.g., 10 to 21 µg/L ethane post-injections) at IR28MW338A suggests degradation to innocuous end products is occurring (**Table 4-4**, **Appendix K**). Given the low concentrations of *Dhc*, this suggests that abiotic RD is likely a more significant contributor to the observed degradation.

4.1.6 Metals

Treatment of contaminated groundwater with ZVI or ISB induces anaerobic conditions that can affect concentrations of redox-sensitive metals, such as iron, arsenic, and manganese, in groundwater. Therefore, metals concentrations were evaluated in the monitoring wells during the baseline and post-RA monitoring events. Iron concentration changes in IR28MW338A and IR28MW938A would be expected to increase during ZVI treatment, as described in the **Section 3.3**. Dissolved iron concentrations were not detected in well IR28MW338A, and a single detection of 17 J µg/L occurred in the 1-month (June 2019) sampling at IR28MW938A (**Table 4-6**). However, ferrous iron was detected during the 6-month (December 2019) sampling event in both monitoring locations using the field test kit (**Table 4-4**). No other significant changes in metals were observed at the monitoring wells.

4.2 RU-C2-3 Performance Monitoring

The COCs exceeding RGs in the RU-C2-3 plume are PCE, TCE, cis-1,2-DCE, VC, CT, and CF for RA performance monitoring wells IR28MW190F, IR28MW300F, IR28MW939F, IR28MW940F and IR28MW941F (**Table 4-5**). As discussed in **Section 3.2**, hydraulic fracturing was successful in delivering 242,249 pounds of ZVI, and 1,088 gallons of LactOil®/ WilclearPlus® into 43 fracture borings shown in **Figure 3-2**. The following sections describe results and evaluation of amendment delivery, geochemical response, and COC treatment for RU-C2-3. Trend charts for COCs, degradation products, microbial biomarkers, and geochemical parameters are provided in **Appendix K**.

4.2.1 Amendment Delivery and Distribution

The following discussion focuses on the initial evaluation of amendment delivery and distribution based on notable field observations made during hydraulic fracturing, 2-D and 3-D visualization of the fracture network generated by tiltmeter monitoring and analysis, and changes in TOC and ferrous iron at performance monitoring wells at RU-C2-3, following the initial amendment emplacement.

The ZVI/ISB treatment approach at RU-C2-3 entailed mapping injections of either high ZVI dose (0.4 wt% of soil) or low ZVI dose (0.25 wt% of soil) with WilclearPlus® and LactOil® based on COC concentrations as shown in **Table 3-1** and **Figures 4-4** through **4-8**. **Table 3-3** also presents the details of the fracture boreholes, including the depth of fracturing, number of fractures, and amendment loading. Generally, fractures were initiated every 3 feet, with four to five fractures completed per borehole.

Field Observations

As shown in **Figures 3-2, 4-6, 4-7** and **4-8**, 43 boreholes were advanced at RU-C2-3, and an amendment slurry of ZVI, LactOil®, and WilclearPlus® were injected in the subsurface. **Table 3-3** summarizes the volumes of amendment and mass loading of ZVI injected into each borehole at each fracture location. The instances of remote (distal from injection borehole) fluid surfacing during low-dose hydraulic fracturing injections are summarized below:

- Low-3: Surfacing of 20 gallons was observed in Low-7 during injection at 29 feet bgs, and less than 1 gallon of seepage was observed in near Low-6 during injection at 25 feet bgs.
- Low-6: Surfacing was observed at monitoring well IR28MW939F during injection at 29, 25, and 21 feet bgs.
- Low-9: Groundwater surfacing of 30 gallons was observed at High-13 during injection at 25 feet bgs.

- Low-11: Surfacing of about 5 gallons was observed at Low-8 during injection at 25 feet bgs, and minor (less than 1 gallon) surfacing was observed at Low-9 during injection at 25 and 21 feet bgs.
- Low-13: Surfacing of about 30 gallons of ZVI-containing fluid was observed at Low-14 during injection at 21 feet bgs.
- Low-15: Minor surfacing (less than 1 gallon) was observed 15 feet south of the boring beneath the foundation slab during injection at 21 feet bgs.
- Low-16: Minor surfacing (less than 1 gallon) was observed approximately 20 feet south of the boring, and 5 to 10 gallons of groundwater surfacing was observed in a drainage swale about 50 feet south of the borehole during injection at 16 feet bgs.
- Low-18: Surfacing was observed about 37 feet south and 10 to 15 feet north of the borehole during injection at 15 feet bgs.
- Low-19: Surfacing of 5 gallons was observed at Low-7 during injection at 25 feet bgs.
- Low-22: Minor ZVI amendment surfacing (less than 1 gallon) was observed along cracks in the concrete during injection at 21 feet bgs.

The instances of amendment surfacing during high-dose hydraulic fracturing injections are summarized below:

- High-1: Groundwater surfacing was observed at High-3 during injection at both 29 and 25.5 feet bgs, and amendment surfacing throughout the pavement was observed 50 feet from High-1 in the eastern-northeastern direction during injection at 22 feet bgs.
- High-3: Amendment surfacing was observed approximately 50 feet east-northeast of the borehole through the pavement during injection at 25.5 feet bgs, and minor seepage (less than 1 liter) of amendment was observed approximately 15 feet from the borehole during injection at 22 feet bgs.
- High-4: Surfacing of 3 gallons of groundwater was observed along the borehole casing during injection at 25 feet bgs; surfacing of 15 gallons of groundwater was observed along the borehole casing and minor ZVI slurry surfacing was observed at High-7 during injection at 21 feet bgs.

Following the amendment emplacement, 1 liter samples of groundwater were collected using a bailer from all monitoring wells in the injection area. Due to the significant ZVI at monitoring wells IR28MW300F and IR28MW941F exhibited by observation that ZVI was still suspended after a 1- to 2-day settling period, these wells were redeveloped to prevent potential ZVI clogging of the well screens.

Tiltmeter

Tiltmeter monitoring is described in **Section 3.2**. Tiltmeter geophysics was used to evaluate the distribution of amendment emplaced by fracturing at 15 boreholes in RU-C2-3. Fractures were performed at specific depth intervals, where Fracture Interval 1 was the deepest and each subsequent interval is shallower than the previous one. **Table 4-2** presents results from the RU-C2-3 tiltmeter data analysis. A summary of the fracture properties for each depth interval, where the Fracture Interval 1 is the deepest for each borehole, is as follows (**Table 4-3**):

- Fracture Interval 1, 26.5 to 29 feet

- Fracture Interval 2, 23.5 to 25.5 feet
- Fracture Interval 3, 20.5 to 22 feet
- Fracture Interval 4, 17 to 19 feet
- Fracture Interval 5, 15 to 16 feet

The tiltmeter geophysics data demonstrated that extents of individual fractures in RU-C2-3 ranged from 17 to 58.6 feet in length and 8 to 47.5 feet in width. The angle of inclination from horizontal (i.e., dip angle) was 2 to 61, with most (49 out of 65) fracture injections dip ranging from 2 to 30 degrees (**Table 4-3**). There did not seem to be correlation between dip angle and the depth of the fracture (**Appendix H**, Geo Tactical Remediation Ltd. 2019).

Tiltmeter data analysis indicated that a pumping efficiency exceeding 80% was achieved at most (53 of 65) fracture intervals subject to hydraulic fracturing and tiltmeter monitoring (**Appendix H**, Geo Tactical Remediation Ltd. 2019). Pumping efficiency is the modeled fracture injection volume (theoretical) divided by the actual volume emplaced. The high pumping efficiency values indicate that only a small portion of the fluid leaked off and that most of the ZVI solids remain in the initiated and propagated fractures.

Because tiltmeter monitoring was not performed at every single injection location, the average fracture length, width, and azimuth from each of the five depth-discrete fracture intervals subject to hydraulic fracturing at RU-C2-3 were calculated (**Table 4-3**). These calculated dimensions were used to simulate the fracture networks at RU-C2-3, as shown in **Figure 4-7**, demonstrating fracture propagation originating from the emplacement of ZVI and ISB slurry beyond the immediate area of the borehole. On average, the fractures propagated 30 to 37 feet in length over four to five fracture intervals.

TOC and Iron

TOC is used as a direct measure for the ISB amendments. Dissolved and ferrous iron are used as the measure for ZVI and anaerobic redox conditions that facilitate iron reduction. Orders-of-magnitude increase in TOC were observed at nearly all performance monitoring wells at RU-C2-3 following the initial ZVI/ISB amendment injection via hydraulic fracturing, except for IR28MW940F (**Table 4-5**). For example, TOC increased from baseline (i.e., pre-hydraulic fracturing) concentrations of less than 3.4 mg/L to approximately 2.6, 490, 720, 11, and 670 mg/L, at IR28MW190F, IR28MW300F, IR28MW939F, IR28MW940F, and IR28MW941F, respectively, 1 month after amendment injection. Concentrations were 2,700 J, 120, 1,100 J, 0.34 U, and 580 mg/L at IR28MW190F, IR28MW300F, IR28MW939F, IR28MW940F, and IR28MW941F, respectively, 6 months after initial amendment injection and 3 months after bioaugmentation.

Similar to TOC, significant increases in dissolved iron concentrations were observed from below detection limit (baseline) to 4,200, 13,000, 180, and 1,900 µg/L at IR28MW300F, IR28MW939F, IR28MW940F, and IR28MW941F, respectively, 1 month after amendment injection (**Table 4-5**). Dissolved iron remained below the method detection limit at IR28MW190F. However, similar to TOC, dissolved iron increased in IR28MW190F 6 months after amendment injection and 3 months after bioaugmentation to 3,700 µg/L. Iron in the other well locations remained high.

Ferrous iron, measured using a field test kit, increased from less than 1 mg/L (baseline) to approximately 2 to 3 mg/L at all four performance monitoring wells at RU-C2-3 (**Table 4-5**). Increases in ferrous iron are likely attributable to both microbially mediated reduction of bioavailable ferric iron in site soil and the emplaced ZVI.

Collectively, these field observations, tiltmeter data, TOC, and ferrous iron measurements indicated that the hydraulic fracturing resulted in successful emplacement of ZVI/ISB amendment at RU-C2-3. Fracture extents exceeding 15 feet and as long as 50 feet were achieved based on tiltmeter data (**Table 4-2**) and evaluation of geochemical conditions at monitoring wells. As shown in **Figures 4-6, 4-7, and 4-8**, complete coverage of the RU-C2-3 treatment area with the injected amendment was attained throughout most of the target treatment volume. However, impacts at boundary performance monitoring well IR28MW940F, located within Building 251, have significantly declined over the 6 months since injections. TOC in IR28MW940F reached 11 mg/L 1-month post-injection and dissolved iron increased to 0.5 µg/L but decreased thereafter. This is consistent with challenges encountered in the field with injecting in the Building 251 area, including access restrictions, problems with collapse of the formation in response to the packers, and significant surfacing of amendment, as described in **Section 3.4**. In addition, a seasonal shift in groundwater gradient resulted in IR28MW940F being up- and cross gradient from the treatment zone as discussed below in **Section 4.2.2**.

4.2.2 Groundwater Gradient and Post-RA Amendment Transport

Figure 4-9 presents the groundwater gradient and direction evaluation based on water levels collected from IR28MW939F, IR28MW940F, and IR28MW941F in December 2018. The estimated gradient direction is shown in the rose diagram (**Figure 4-9**, inset) and presents the magnitude and direction of hydraulic gradients for baseline, June 2019, August 2019, and December 2019 sampling events, estimated according to the three-point method of analysis described in *3PE: A Tool for Estimating Groundwater Flow Vectors* (EPA 2014).

During baseline, June 2019, and August 2019 sampling events, the groundwater gradient was northeasterly towards IR28MW940F and Building 251. In December 2019 (3 months post-RA), the water level in IR28MW939F was recorded to be approximately three feet lower than at past events. Thus, the estimated hydraulic gradient in December 2019 was northwesterly, towards IR28MW939F.

Figure 4-9 illustrates a seasonal shift in hydraulic gradient in the F-WBZ at RU-C2-3 with gradient direction northeasterly in summer and fall and shifting northwesterly in winter. This shift in gradient can explain analytical results in boundary well IR28MW940F, which appeared to be downgradient and impacted by amendment injections in the 1-month, June 2019 and 3-month, August 2019 sampling events but not in the 6-month, December 2019 data, as shown in **Table 4-5**. Geochemical and COC results are discussed further in **Sections 4.2.3 and 4.2.5**.

4.2.3 Geochemical Parameters

As discussed in **Section 2.7**, geochemical parameters are evaluated to determine if conditions are suitable to support COC degradation. For biotic COC degradation to occur, redox conditions must support processes (e.g., anaerobic RD), and pH must be in an optimal range. Multiple lines of evidence were used to assess geochemical conditions before and after amendment injections.

Redox Conditions

Sulfate, ferrous iron, DO, ORP, and methane are redox parameters used to evaluate the degree to which reducing conditions are established at a location. RD of PCE and TCE to cis-1,2-DCE generally occurs under iron-reducing to sulfate-reducing conditions. Complete dechlorination to ethene and ethane typically occurs under sulfate-reducing to methanogenic conditions. Thus, understanding redox conditions provides key insight into the potential for anaerobic RD to occur at a site.

In addition, redox conditions often control the mobility and subsequent concentration in groundwater of redox-sensitive metals such as iron, manganese, and arsenic. Under reducing conditions, these metals are

transformed from their oxidized (and immobile) states to their more soluble, reduced forms. In addition, many metals that are not redox sensitive are sorbed to iron and manganese oxyhydroxides, which may dissolve under reducing conditions, releasing sorbed metals. If site soil/sediments contain redox-sensitive metals, elevated concentrations in groundwater will be observed in areas with reducing conditions.

The concentrations of various electron acceptors are discussed below to assess the redox conditions within RU-C2-3 performance monitoring wells. Methanogenic conditions, typically ideal for complete RD of PCE and TCE to ethene or ethane, are indicated by the absence of oxygen, sulfate, and nitrate and by the presence of methane and dissolved iron. In addition, methane production is used as a surrogate for ideal conditions for RD because methanogens and *Dhc* spp., one key group of bacteria that reductively dechlorinate TCE to ethene, generally require the same conditions (presence of hydrogen and carbon, reducing conditions, and pH greater than 6) for growth and activity. Therefore, production of methane often coincides with production of ethene or ethane from RD.

Overall, significant changes in redox conditions were observed at nearly all RU-C2-3 performance monitoring wells within 6 months following the initial amendment injection (**Table 4-5**). Geochemical conditions typical of aerobic to nitrate-reducing conditions were initially observed at IR28MW190F, IR28MW300F, IR28MW939F, and IR28MW941F at baseline as evident by elevated DO (greater than 1 mg/L), and elevated nitrate concentration (near or greater than 1 mg/L). Following the ZVI/ISB amendment injection, DO decreased significantly to below 0.1 mg/L in all four aforementioned monitoring wells in December 2019. In addition to the DO depletion, negative ORPs, complete nitrate depletion, elevated ferrous iron (exceeding 1 mg/L) and manganese (greater than 1 mg/L), near or complete sulfate reduction, and orders of magnitude increases in methane (greater than 1 mg/L) were observed within the monitoring period.

Collectively, geochemical conditions typical of methanogenesis were observed at IR28MW190F, IR28MW300F, IR28MW939F, and IR28MW941F in December 2019, which is approximately 6 months following the initial ZVI/ISB amendment injections. Highly reducing conditions characteristic of methanogenesis are generally expected following ZVI/ISB amendment injections and are conducive to microbially-mediated (biotic) RD (ISB) and abiotic dechlorination (ZVI-driven).

In contrast to IR28MW190F, IR28MW300F, IR28MW939F, and IR28MW941F, minimal TOC was distributed to IR28MW940F, likely suggesting less efficient amendment distribution in this area of the plume, as mentioned in **Section 4.2.1**. Changes in redox conditions were most significant in the 1-month (June 2019) sampling event, with observed TOC of 11 mg/L and reduced levels of both ORP and sulfate (concentrations reduced from 28 to 12 mg/L) (**Table 4-5**). DO decreased to below 0.5 mg/L and was maintained low for the 6 months following the amendment injection. Rebound in other parameters, such as nitrate (greater than 1 mg/L) in the 3-month and 6-month (December 2019) events was observed. In addition, no significant increases in ferrous iron or manganese were observed. Methane increased over the monitoring period, with maximum, albeit relatively low, concentrations (0.31 mg/L) as of the 6-month (December 2019) event. Collectively, geochemical conditions typical of anoxic to nitrate-reduction were observed at IR28MW940F 6 months following the initial amendment injections. Results reflect both the limited ability to inject amendment and the shift in hydraulic gradient observed between the 1-month and 3-month and 6-month sampling events (as discussed in **Section 4.2.2**).

Water Quality Parameters

Alkalinity is used as an indirect parameter to evaluate increases in microbial activity following amendment injection. In general, increased alkalinity suggests that anoxic microbial activity has been enhanced, generating volatile fatty acids (VFAs) from fermentation of organic carbon (e.g., lactate amendment). In

addition, microbial metabolism generates high levels of carbon dioxide, which gets converted to bicarbonate alkalinity in groundwater systems.

Alkalinity measured prior to amendment injections ranged from 81 to 200 mg/L (**Table 4-5**). Results from the 6-month post-RA sampling event show alkalinity levels ranging from 1,000 mg/L to 3,100 mg/L in IR28MW190F, IR28MW300F, IR28MW939F, and IR28MW941F, showing substantial increases compared to baseline data. For IR28MW940F, alkalinity remained similar (160 to 180 mg/L) for all sampling events. Increased alkalinity suggests that anoxic microbial activity has been enhanced, generating VFAs from fermentation of organic carbon (e.g., lactate amendment).

pH is a key factor influencing both potential for and rates of biotic and abiotic COC degradation reactions, and it can influence the mobility of metals. A pH below 6 will inhibit the bacteria capable of complete RD to ethene, primarily the *Dhc* spp., with complete inhibition at pH of 5.5 or less. pH was generally measured between 6 and 8 standard pH units in all five performance monitoring wells during baseline and post-RA sampling events (**Table 4-5**). In IR28MW941F, the baseline pH measured above 9 pH units; however, within 1 month following RA, this dropped below 8 pH units.

4.2.4 Microbial Biomarkers

As described in **Section 3.2.4**, bioaugmentation occurred in August 2019 shortly after the 3-month post-RA sampling event. *Dhc*-containing bioaugmentation cultures were injected into IR28MW190F, IR28MW300F, IR28MW939F, and IR28MW941F, followed by anoxic water.

During post-RA monitoring, deoxyribonucleic acid (DNA) was extracted from groundwater samples collected from four RU-C2-3 performance monitoring wells to evaluate the presence of microbial populations capable of degrading PCE and TCE to innocuous end products. DNA analysis using quantitative polymerase chain reaction [qPCR]) was used to estimate the number of gene copies per milliliter groundwater of chlorinated COC-degrading bacteria. Using qPCR methods, techniques have been developed to identify four genes associated with *Dhc*.

First is the 16S rRNA gene, which is used as the general marker for evaluating all strains of *Dhc* present in a sample. Three functional genes, *tceA*, *vcrA*, and *bvcA*, associated with differing reductive dechlorinating capacities, also were evaluated. Reductase gene *tceA* was isolated from *Dhc ethenogenes* strain 195, which reduces PCE or TCE to cis-1,2-DCE and VC in energy-yielding reactions but only reduces VC to ethene in a co-metabolic reaction, which may result in VC accumulation in the field. Reductase gene *vcrA* was isolated from *Dhc* train VS and degrades PCE and TCE energetically all the way to ethene. Reductase gene *bvcA* was isolated from *Dhc* strain BAVI and only degrades PCE or TCE co-metabolically and energetically degrades *Dhc* and VC to ethene. Hence, the discussion and evaluation of effective RD of COCs present at RU-C2-3 is primarily focused on the *Dhc* population and the functional *vcrA*.

Typically, *Dhc* concentrations greater than 10^3 to 10^4 gene copies per milliliter are necessary for efficient dechlorination of 1,2-DCE and VC to occur. Similarly, functional genes (specifically, *bvcA* or *vcrA*) are required at robust populations for dechlorination of DCE and VC.

Baseline data for microbial parameters were collected in June 2019, prior to bioaugmentation. In all four bioaugmented wells, *Dhc* and reductase genes were not detected or were present at very low concentrations (**Table 4-5**). Concentration remained low after the amendment injection at the 1- and 3-month sampling events. Shortly after the 3-month sampling event, bioaugmentation was performed. Following bioaugmentation, *Dhc* and reductase gene concentrations increased to concentrations on the order of 10^5 gene copies per milliliter in all four bioaugmented wells observed during the 6-month post RA sampling event, 3 months after bioaugmentation. Functional gene copies also increased, with *vcrA* being present at

the highest concentrations. These data indicate that sufficient concentrations of dechlorinating microorganism populations were delivered to the plume and that subsurface conditions have been optimized to sustain these microbial populations such that biodegradation of the chlorinated COC mass is optimized.

4.2.5 COCs

Performance monitoring wells were used to assess the ZVI/ISB treatment at RU-C2-3 within the first 6 months following amendment injection. The goal is to degrade COCs to innocuous end products (ethene, ethane, carbon dioxide, water, chloride). TCE and CT are considered parent compounds associated with spills of the original wastes, whereas cis-1,2-DCE, trans-1,2-DCE, VC, CF, and methylene chloride are considered degradation byproducts. Trend charts for COCs, degradation products, and geochemical parameters are presented in **Appendix K**. COC concentrations are presented both on a mass basis and a molar basis. **Figure 4-10** presents results for RU-C2-3 COCs.

The molar concentrations are calculated to evaluate chemical mass balances during degradation as 1 mole of TCE degrades to 1 mole of DCE, 1 mole of VC, and 1 mole of ethene if RD is the only degradation mechanism. Evaluating concentrations on a molar basis allows for direct evaluation of the degree to which RD is progressing during implementation of the remedy and the mass balance between parent and daughter products. As presented in **Table 4-5** and indicated on the trend charts in **Appendix K**, the wells within the ZVI/ISB treatment volume exhibit substantial evidence of biotic and abiotic degradation.

Concentrations and Trends

RU-C2-3 COCs include TCE, CT, and CF. This section describes general trends in the data for each COC for the baseline and 1-, 3-, and 6-month post-RA sampling events. Results from each event are presented in **Table 4-5** and trend charts are presented in **Appendix K**.

Prior to amendment injections, TCE exceeded the RG (2.9 µg/L) in all wells, except for IR28MW940F. The highest TCE concentration was measured in IR28MW941F at 7,800 µg/L, and concentrations at IR28MW190F, IR28MW300F, IRMW939F, and IR28MW940F were significantly lower, at 4.2, 9.9, 14, and 0.23J µg/L, respectively.

Following the RA, TCE concentrations over the post-RA monitoring period (June 2019 to December 2019) saw substantial declines. In December 2019 (6-month post-RA), TCE was not detected in any RU-C2-3 performance monitoring well, except for IR28MW941F. In this well, TCE had decreased by two orders of magnitude (TCE was detected at 73 µg/L) by the 6-month post-RA sample. While concentrations still exceed both the RG and ISB ATC for TCE (29 µg/L), continued decreasing trends in concentrations in conjunction with optimal geochemical conditions are expected within and downgradient from the treatment volume. In IR28MW190F, 6-month post-RA nondetect results for both PCE and TCE were reported at 10 UJ µg/L.

Prior to the RA, CT exceeded the ATC (5 µg/L) and the RG (0.5 µg/L) in all RU-C2-3 performance monitoring wells, with a maximum concentration of 120 J µg/L measured in IR28MW190F. Following the RA, CT concentrations decreased rapidly and were below the limit of detection by December 2019 in all wells except IR28MW940F. CT initially declined in IR28MW940F and was below the ATC at this well (2.9 µg/L) in the 1-month monitoring event but increased in the 3- (16 µg/L) and 6-month (25 µg/L) events.

Prior to the RA, CF exceeded the ATC (7 µg/L) in all wells except IR28MW939F. A maximum concentration of 58 µg/L was detected in IR28MW190F. CF trends behaved similarly to CT trends, with a general decrease in concentration during the post-RA performance monitoring period, except in IR28MW940F. CF concentrations in this well did not significantly change during the post-RA monitoring period (**Table 4-5**).

Ultimately, the RA resulted in a significant decrease in COC mass within the RU-C2-3 plume, especially with respect to TCE and CT.

Degradation Products

The RA approach for RU-C2-3 was a combined ZVI/ISB remedy designed to create sufficiently reducing conditions within the aquifer to promote both abiotic and biotic RD of CT, CF, and TCE. Degradation of these chemicals occurs via several transformation steps, often producing degradation products such as lesser chlorinated methylene chloride, cis-1,2-DCE, and VC (**Figures 2-9 and 2-10**). Complete transformation of COC via these degradation pathways result in fully dechlorinated, innocuous degradation products, including ethene, ethane, acetylene, methane, and carbon dioxide.

In RU-C2-3 performance monitoring wells, TCE degradation product concentrations were largely low or nondetect, except in IR28MW941F, which had relatively high baseline cis-1,2-DCE (180 µg/L) and detected VC (0.61J µg/L), ethene (3.5 µg/L), and ethane (9 µg/L). During the post-RA performance monitoring period, cis-1,2-DCE and VC increased in IR28MW941F, reaching 990 µg/L and 33 µg/L, respectively, in the 6-month (December 2019) sampling event and trans-1,2-DCE and 1,1-DCE were detected at low levels. Ethane increased substantially in IR28MW300F (from 3U to 22J µg/L), IR28MW939F (0.7J to 140 µg/L), and IR28MW941F (9 to 190 µg/L) during the post-RA monitoring period.

In general, the relatively high amounts of ethane generated at the 1-month monitoring event without increases in cis-DCE or VC suggests that abiotic beta elimination (via ZVI) was the predominant degradation mechanism for TCE, which does not generate the cis-DCE or VC intermediates (see **Figure 2-9**). The biotic pathway tends to produce more cis-DCE, VC and ethene. Following bioaugmentation, biotic degradation became more prevalent with elevated concentrations of cis-DCE (up to 990 µg/L), VC (33 µg/L), and ethene (88 µg/L) observed at IR28MW941F. Collectively, these parameters indicate that TCE is degrading via abiotic and biotic RD to innocuous end products. **Appendix K** presents trend charts with mass and molar concentrations. Molar concentration graphs generally reflect the transition in chloroethene mass from parent COC to daughter degradation products expected during biotic RD.

Post-RA concentrations of CT degradation by-products, methylene chloride and chloromethane, increased slightly in several wells; however, most detections were below 5 µg/L, and December 2019 data for these parameters are largely nondetect. Methane levels significantly increased during the post-RA period; however, that is largely attributable to methanogenesis from injection of lactate and LactOil®. Molar concentration graphs in **Appendix K** do not reflect a significant transition from parent COC mass to degradation daughter product mass. High proportions of CF are apparent but are biased high in December 2019 data because of high detection limits, as discussed in **Section 3.5**.

4.2.6 Metals

Iron concentration changes are indicative of the ZVI treatment. Concentrations of dissolved iron increased by up to three orders of magnitude in IR28MW300F, IR28MW939F, IR28MW940F, and IR28MW941F between baseline and post-RA monitoring events (**Table 4-6**). This trend indicates a successful delivery of ZVI to these locations. Concentrations remained high in IR28MW300F, IR28MW939F, and IR28MW941F throughout the monitoring period.

Delayed increases in dissolved iron concentration in IR28MW190F were consistent with the lag in the other amendment and geochemical parameters (**Sections 4.2.1 and 4.2.3**). Substantial increases in dissolved iron were not observed until the 6-month (December 2019) post-RA sampling event when concentrations increased from below the level of detection (LOD) to 3,700 µg/L (**Table 4-6**). Based on data evaluation, it

is likely that the hydraulic fractures did not directly intersect this well screen but did deliver amendments close to this well. In addition, bioaugmentation influenced the geochemistry observed at this well.

Iron concentrations in IR28MW940F increased from below the LOD during baseline to 140 to 180 µg/L in the 1- and 3-month sampling events. However, concentration declined to 32J µg/L by the 6-month sampling events (**Table 4-6**).

Concentrations of other metals were tracked to evaluate the impacts of the RA. Zinc remained below its RG of 81 µg/L. Dissolved chromium was generally observed at relatively low concentrations (<10 µg/L) for most locations at most timepoints with two notable exceptions. At IR28MW190F, concentrations increased from approximately 23–24 µg/L during all previous sampling events to 120 µg/L during the 6-month (December 2019) sampling event (**Table 4-6**). Results include trivalent and hexavalent chromium, and, given the prevalence of highly reduced conditions associated with treatment, it is likely most soluble chromium is present as trivalent chromium as opposed to the more toxic hexavalent chromium. However, speciation is required to verify the form of chromium present.

Slight increases in arsenic from below the LOD to 8.2 and 3.6 µg/L were observed in IR28MW190F and IR28MW300F. Increases in other redox-sensitive metals such as barium, cobalt, manganese, nickel, and vanadium concentrations were observed after amendment injections. In general, these transient increases in metal are expected to be only temporary and concentrations will decline post-RA when conditions become more oxidized.

4.2.7 Other Chemicals

The analytical performance monitoring identified other chemicals that can affect interpretation of the RA performance at RU-C2-3. Specifically, other chemicals identified include:

- 1,1,2-Trichloro-1,2,2-Trifluoroethane (chlorofluorocarbon [CFC]-113)
- Trichlorofluoromethane (CFC-11)
- Dichlorodifluoromethane (CFC-12)
- 2-butanone (methyl ethyl ketone [MEK])

Various chlorofluorocarbons (CFCs) were detected at relatively high concentrations in RU-C2-3. CFCs do not occur naturally and were produced in large quantities by a couple of companies in the United States (NOAA 2020; EPA 2020b). TCE was sometimes a chemical intermediate in the process of creating some CFCs (Sullivan and Krieger 2001). In addition, large quantities of CT were used to produce CFC-11 and CFC-12. Therefore, the source of these CFCs is likely a source of CT. In general, the identified CFCs are recalcitrant in aerobic aquifers. However, under anaerobic conditions Freons can all undergo biotic anaerobic RD through a variety of mechanisms, including halorespiration, where microorganisms use them as terminal electron acceptors. Typically, the required redox levels need to be at least as low as those required for iron or sulfate reduction, although methanogenic conditions are ideal for complete degradation of intermediates. In addition, the presence of other chemicals that are subject to RD can affect dechlorination of target COCs through consumption of available carbon, nutrients and electrons, potentially inhibitory effects, or toxicity to COC-degrading microorganisms. Therefore, degradation of CFCs was tracked along with the COCs. In general, the post-RA data have shown substantial reductions on concentrations of all CFCs with production of degradation by-products indicating concentration reductions are a direct result of biotic and abiotic degradation.

1,1,2-Trichloro-1,2,2-Trifluoroethane (CFC-113) was detected at relatively high concentration of 5,100 µg/L in RU-C2-3 well IR28MW941F during baseline to 930 µg/L at the 6 month post-RA sampling event

(**Table 4-7, Appendix J and K**). Other detections were observed within the RU-C2-3 VOC plume at the wells IR28MW939F, IR28MW190F, and IR28MW300F.

CFC-113 is a Freon with low flammability and low toxicity. It is noncarcinogenic. Historically, it was widely used as a cooling agent in refrigerants and air conditioners, aerosol propellant, and cleansing agent for electrical and electronic components, fabrics, and metals (National Center for Biotechnology Information [NCBI] 2020a). CFC-113 has been shown to biodegrade under two dechlorination pathways under anaerobic conditions where stepwise RD is supported producing dichloro-1,1,2 trifluoroethane (Freon 123a and 123b), 1-chloro-1,2,2-trifluoroethane (Freon 133), and 1,1,2-trifluoroethane (Freon 143) as intermediates. In the second pathway, stepwise dechlorination produces a double carbon-carbon bond at the second step, producing 1,2-dichloro-1,1,2 trifluoroethane (Freon 123a), the double-bonded chlorotrifluoroethene (Freon 1113), and trifluoroethane as intermediates (Field and Sierra-Alvarez 2004).

CFC-113 also is degraded through treatment with ZVI, which can dechlorinate the chemical to Freon 1113, HCFC123a, Chlorotrifluoroethylene with further degradation to acetate, hydrogen fluoride, hydrochloric acid, or ethene and ethane (Mohn and Tiedje 1992).

Substantial reductions in CFC-113 were observed in all monitoring wells with CFC-113 detections in response to the RU-C2-3 remedial action. CFC-113 at the well IR28MW941F was reduced by over 80% as a result of the RA (**Table 4-7**). Detections found in wells IR28MW190F, IR28MW300F, and IR28MW939F during the baseline sampling event were all nondetect by the 6-month (December 2019) post-RA sampling event.

Trichlorofluoromethane (CFC-11) was detected within the RU-C2-3 plume at concentrations of 850 and 510 µg/L in wells IR28MW939F and IR28MW941F during pre-RA baseline sampling (**Table 4-7**). CFC-11 is a noncarcinogenic chemical with low flammability and low toxicity. Historically it has been used as a refrigerant, a solvent, in fire extinguishers, a chemical intermediate, and a blowing agent (NCBI 2020c). Under anaerobic conditions, biotic RD processes occur producing dichlorofluoromethane (HCFC-21) and carbon monoxide. CFC-11 can be degraded abiotically through ZVI reduction, producing HCFC-21, HCFC-31, methane, carbon monoxide, or formate as intermediates, as described by Sonier et al. (1994).

CFC-11 concentrations decreased in response to the RU-C2-3 RA. The 6-month (December 2019) sampling results indicated concentrations of 9 and 26 µg/L in wells IR28MW939F and IR28MW941F, respectively. Elevated concentration of 47 µg/L was detected during baseline 2017 sampling in IR28MW300F; however, the concentration post-RA has been following the same decreasing trend with the only other detection of 4.8 µg/L in June 2019 and nondetects in all the sampling events afterwards. CFC-11 concentrations have been below 4 µg/L for IR28MW940F and IR28MW190F.

Dichlorodifluoromethane (CFC-12) was detected in well IR28MW941F at a concentration of 91 µg/L during baseline sampling and not detected during 6-month (December 2019) post-RA sampling (**Table 4-7**). CFC-12 was detected below 0.5 µg/L at IR28MW300F and IR28MW939F during the baseline sampling and 1-month post-RA sampling events. At IR28MW940F, CFC-12 was detected below 0.5 µg/L for all sampling events. CFC-12 is noncarcinogenic, Freon used as a refrigerant, foam blowing agent, and solvent in the aerospace and electronics industries. It is also recalcitrant under aerobic conditions but can be biodegraded anaerobically through RD processes, producing lesser chlorinated compounds such as HCFC-21, HCFC-31, and HCFC-22 as intermediates (NCBI 2020b).

Post-RA sampling indicated production and increasing concentrations of 2-butanone, also known as MEK. During anaerobic fermentation of complex carbon sources, such as emulsified vegetable oil, MEK is produced. Therefore, the RA may temporarily raise groundwater concentrations for these intermediates.

However, MEK is readily biodegradable and concentrations will decline as treatment progresses and amendments are consumed, and concentrations become depleted.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This section discusses the effectiveness of the RAs toward achieving the groundwater RAOs per the Final Parcel C ROD (Navy 2010) and described in **Section 1.2**.

Concentrations of COCs in groundwater were compared to the RGs and ATCs listed on **Table 1-2**. The RGs for COCs in groundwater are presented in the Parcel C Final ROD *Table 4* (Navy 2010) and **Attachment 1** of this I-RACR, and are based on potential residential exposure via vapor intrusion and may be superseded by future action levels for soil gas, based on the results of future soil gas surveys. As discussed in the RDDBR (KCH 2012), groundwater treatment was focused on the A-aquifer to minimize the vapor intrusion risk. The groundwater remedy consisted of active treatment using ZVI or ISB to be followed by MNA to achieve RGs. **Section 3** provides detail on the implementation of the active treatment conducted at RU-C1-1 and RU-C2-3.

Following the RA, the effectiveness of the active groundwater RA was evaluated by comparing the post-RA performance monitoring results, which includes 1-month, 3-month, and 6-month sampling against the ATC (**Section 4, Appendix K**). Additional 9-month and 12-month performance monitoring will be conducted by the BGMP per the Parcel C Remedial Action Monitoring Plan (RAMP) (IGI 2020a). The subsequent performance monitoring will be conducted by the BGMP to establish post-RA performance trends and evaluated as part of the Remedial Action Monitoring Reports (RAMRs, IGI 2020b).

5.1 Groundwater Treatment at RU-C1-1

As discussed in **Section 3**, groundwater treatment at RU-C1-1 included advancing three hydraulic fracturing boreholes and delivering amendment containing 6,871 pounds of ZVI and 45 gallons of emulsified vegetable oil (LactOil)[®] and sodium lactate (WilclearPlus[®]) at target treatment depths of 7 to 15 feet bgs. Hydraulic fracturing in RU-C1-1 was intended to deliver amendments to promote abiotic and biotic RD of PCE and its lesser chlorinated degradation products within an area that exceeded ATC at boring RUC11HPT04. As shown in **Figure 3-1**, performance monitoring well IR28MW338A is located beyond the plume boundary and just outside of the treatment area. As discussed in **Section 4.0**, groundwater RA activities were successfully conducted per the RAWPA (ECC-Insight and CDM Smith 2019a) and amendment distribution was successful within the treatment area. Because hydraulic fracturing was performed in unconsolidated material for this plume, the fracture fluid is expected to propagate into the formation rather than stay within the original fracture network. The amendment dissolution and advective transport of the amendment within the aquifer expands the treatment area over time beyond the original fracture network presented in **Figure 4-1**.

As shown in **Table 4-4**, all COCs in IR28MW938A met RGs at baseline. In addition, IR28MW338A, located north of the hotspot RUC11HPT04, had COC concentrations above RGs but below ATC (**Figure 4-3**). The injections delivered amendments at a 12-foot extent around three injection points surrounding RUC11HPT04, which was confirmed by tiltmeter analysis. Due to the small area of the RU-C1-1 plume above the ATC and that the performance monitoring wells IR28MW338A and IR28MW938A were just outside of the injection zone, minimal changes to geochemistry and COC concentrations were observed within these performance monitoring wells during the 6-month post-RA monitoring period. Because COCs within the monitoring wells are below ATC, the plumes will continue to be monitored via performance monitoring through the BGMP to establish COC trends and transition to MNA monitoring per the RAMP (IGI 2020a). Recommendations for ongoing activities for this area, including groundwater monitoring, are provided in **Section 5.3**.

5.2 Groundwater Treatment at RU-C2-3

As discussed in **Section 3**, groundwater treatment at RU-C2-3 included advancing 43 hydraulic fracturing boreholes and delivering amendment containing 242,249 pounds of ZVI and 1,088 gallons of emulsified vegetable oil (LactOil®) and sodium lactate (WilclearPlus®) at target treatment depths of 12 to 29 feet bgs. Hydraulic fracturing in RU-C2-3 was intended to deliver amendments to promote both abiotic and biotic RD of TCE and CT and their lesser chlorinated degradation products within an area that exceeded ATC, as shown in **Figure 4-6**.

Performance monitoring wells within and on the RU-C2-3 boundary were monitored before and 1, 3, and 6 months after the RA injections. As discussed in **Section 4.0**, groundwater RA activities were successfully conducted per the RAWPA (ECC-Insight and CDM Smith 2019a) and multiple lines of evidence have demonstrated successful amendment delivery and subsurface conditions conducive to abiotic and biotic degradation of COCs in RU-C2-3. As discussed in **Section 4.2.1**, amendment distribution was largely successful within the treatment volume as indicated by visual observations, tiltmetering data, iron and TOC levels, and other geochemistry changes during the post-RA monitoring period. Because hydraulic fracturing was performed in weathered bedrock for this plume, the fracture fluid is expected to propagate through the emplaced fracture network (**Figures 4-6 through 4-8**). The amendment dissolution and advective transport within the aquifer further expands the treatment volume over time beyond the original fracture network presented in **Figures 4-6 and 4-7**. Within the hotspot area near IR28MW941F, a two order of magnitude decrease in TCE concentrations were observed with substantial increases in degradation by products including the innocuous ethene and ethane (**Table 4-5**). TCE concentrations were just above ATC and are expected to continue to decline. Likewise, cis-1,2-DCE, VC, and CT are above ATC, but declining COC trends are expected to continue. Collectively, decreasing COC trends, increasing COC daughter product trends, high levels of *Dhc* and reductase/functional genes, and highly reducing geochemical conditions indicate that the RA was successful in promoting the removal of COC mass from RU-C2-3 via abiotic and biotic degradation mechanisms (**Table 4-5, Figure 4-10**).

Substantial difficulties were realized in the injections conducted within Building 251 at the original Low-23 borehole planned near IR28MW940F. Instability and collapse of the formation resulted in the inability to set the packers necessary for fracturing. As such, the borehole was moved approximately 90 feet west outside the building because of access limitations within the building. Initial results indicated some influence of the injection conducted at Low-22 at IR28MW940F. However, geochemical conditions have since rebounded along with CT concentrations to levels above ATC. It is anticipated that concentrations in this area will eventually decline as impacts from the treatment outside the building migrate to this location. The Navy will continue to conduct groundwater monitoring as part of the BGMP to evaluate rebound at all Parcel C groundwater plumes, including RU-C1-1 and RU-C2-3, to monitor the long-term effectiveness of the remedy. However, seasonal shifts in groundwater gradient may impact the long-term trends in COCs as discussed in **Section 4.2.2**.

5.3 Recommendations and Ongoing Activities

Remedy in place has been achieved at plumes RU-C1-1 and RU-C2-3 with substantial reductions in COCs achieved. Continued post-RA monitoring will be conducted by the BGMP per the RAMP (Indus 2020a) with results included in future Parcel C RAMRs (e.g. IGI, 2020b). Continued evaluations of groundwater trends post-RA are recommended as follows:

- Conduct 9-month and 12-month post-RA sampling and then semiannual BGMP sampling of RU-C1-1 monitoring wells IR28MW938A and IR28MW338A

- Conduct 9-month and 12-month post-RA sampling and then semiannual BGMP sampling of RUC2-3 monitoring wells IR28MW190F, IR28MW300F, IR28MW939F, IR28MW940F, and IR28MW941F

The recommended suite of analyses includes:

- Purge parameters (DO, ORP, pH, conductivity)
- Anions (full suite EPA Method 300.0)
- TOC (EPA Method 9060)
- Total Metals (EPA Method 6010B/7470A)
- Hexavalent Chromium (RU-C2-3 only, EPA Method 7199)
- VOCs (EPA Method 8260B)
- Methane/ethane/ethene/acetylene (RSK-175)
- *Dhc* spp. *vcrA*, *bvcA*, *tceA* (qPCR, lab-specific method)
- Water levels to continue to evaluate seasonal gradient shifts in RU-C2-3

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6.0 REFERENCES

- The Alliance Compliance Group Joint Venture (Alliance). 2015. *Internal Draft Remedial Action Work Plan, RU-C2 - Addendum. Hunters Point Naval Shipyard, San Francisco, California.* May.
- . 2013. *Remedial Action Work Plan, RU-C2. Hunters Point Naval Shipyard, San Francisco, California.* March.
- . 2012. *Pre-Design Investigation Technical Memorandum. Hunters Point Naval Shipyard, San Francisco, California.* July.
- Aptim Federal Services, LLC (APTIM). 2018. *Final Interim Remedial Action Completion Report, Parcel C Remedial Action, Remedial Units C1, C4, and C5, and Building 241 (Exclude C2), Hunters Point Naval Shipyard, San Francisco, California.* March.
- Bonilla, M.G. 1998. *Preliminary geologic map of the San Francisco South 7.5' quadrangle and part of the Hunters Point 7.5' quadrangle, San Francisco Bay area, California: A digital database.* U.S. Geological Survey Open-File Report 98-354.
- California Department of Transportation (Caltrans). 1996. *Manual of Traffic Control for Construction and Maintenance Work Zones.*
- California Department of Toxic Substances Control. (DTSC). 2001. *Information Advisory, Clean Imported Fill Material.* October. Available Online at:
http://www.dtsc.ca.gov/Schools/index.cfm#Fact_Sheets_and_General_Information
- CB&I Federal Services LLC (CB&I). 2015a. *Final Technical Memorandum, Groundwater and Soil Vapor Characterization in Support of Parcel C Remedial Action, Remedial Unit C5, Hunters Point Naval Shipyard, San Francisco, California.* August.
- . 2015b. *Draft Site Conditions Report, Area of Concern 28-H, Parcel C, Hunters Point Naval Shipyard, San Francisco, California.* August.
- . 2015c. *Final Work Plan Addendum 01, Parcel C Remedial Action, Remedial Units C1, C4, and C5, and Building 241 (Excludes C2), Hunters Point Naval Shipyard, San Francisco, California.* October.
- . 2014. *Final Soil Vapor Extraction System Operation and Maintenance Plan, Parcel C Remedial Action Remedial Units C1, C4, and C5, and Building 241, Hunters Point Naval Shipyard, San Francisco, California.* August.
- . 2013. *Final Work Plan, Parcel C Remedial Action, Remedial Units C1, C4, and C5, and Building 241 (Excludes C2), Hunters Point Naval Shipyard, San Francisco, California.* July.
- CDM Smith. 2012. *Final Treatability Study Completion Report, Remedial Unit-C5, Building 134, Hunters Point Naval Shipyard, San Francisco, California.* January 27.

ChaduxTt. 2011. *Revised Final Memorandum: Approach for Developing Soil Gas Action Levels for Vapor Intrusion Exposure at Hunters Point Naval Shipyard, Hunters Point Naval Shipyard, San Francisco, California*. December 2.

ECC-Insight and CDM Smith. 2019a. *Final Remedial Action Work Plan Addendum Parcel C Remedial Units C1, C2, C4, and C5, Hunters Point Naval Shipyard, San Francisco, California*. April.

———. 2019b. *Final Parcel C Soil Vapor Extraction System Operation and Maintenance Summary Report, Hunters Point Naval Shipyard, San Francisco, California*. February.

———. 2017. *Final Remedial Action Work Plan Parcel C Remedial Units C1, C2, C4, and C5, Hunters Point Naval Shipyard, San Francisco, California*. November.

———. 2016. *Final Accident Prevention Plan Parcel C Remedial Units C1, C2, C4, and C5 and Building 134 Area, Hunters Point Naval Shipyard, San Francisco, California*. May.

Fetter, C. W. 2001. *Applied Hydrogeology (4th edition)*. Upper Saddle River, NJ: Prentice Hall, 598.

Field, J.A., and R. Sierra-Alvarez. 2004. *Biodegradability of chlorinated solvents and related chlorinated aliphatic compounds*. *Reviews in Environmental Science and Bio/Technology* 3.3: 185-254.

Geo Tactical Remediation Ltd. 2019. *Final Report on the Emplacement of ZVI Using Hydraulic Fracturing Technology, Parcel C Remedial Units, Hunters Point Naval Shipyard*. Prepared for Insight Environmental, Engineering & Construction, Inc. on behalf of Frac Rite Remediation Inc. August.

Grosterm, A. M. Duhamel, S. Dworatzek, and E.A. Edwards. 2010. *Chloroform Respiration to Dichloromethane by a Dehalobacter population*. *Environmental Microbiology*, 12, 4: 1053–1060.

Indus General Inc. (IGI). 2020a. *Final Remedial Action Monitoring Plan Parcel C, Remedial Units C1, C2, C4 and C5, Hunters Point Naval Shipyard, San Francisco, California*. March.

———. 2020b. *Draft Spring 2019 Semiannual Remedial Action Monitoring Report for Parcel C, Remedial Units C1, C2, C4, and C5, Hunters Point Naval Shipyard, San Francisco, California*. February.

IT Corporation (IT). 2002. *Draft Phase II Soil Vapor Extraction Treatability Study Report, Building 272, IR-28, Parcel C, Hunters Point Shipyard, San Francisco, California*. February.

———. 2001. *Draft Treatability Study Report, Soil Vapor Extraction Treatability Study, Building 134, Parcel C, Hunters Point Shipyard, San Francisco*. December.

ITRC. 2008. *In Situ Bioremediation of Chlorinated Ethene: DNAPL Source Zones*. June. Available online: <https://www.itrcweb.org/Guidance/GetDocument?documentID=12>

ITSI. 2005. *Final Zero-Valent Iron Injections Treatability Study Report Building 272, Parcel C, Hunters Point Shipyard, San Francisco, California*. April.

Justicia-Leon, S.D., K.M. Rialahti, E.E. Mack, and F.E. Löffler. 2012. *Dichloromethane fermentation by a Dehalobacter sp. in an Enrichment Culture Derived from Pristine River Sediment*. *Applied Environmental Microbiology*, 78, 4: 1288-1291.

- Kleinfelder and CH2MHILL joint venture (KCH). 2012. *Final Remedial Design and Design Basis Report for Parcel C, Hunters Point Naval Shipyard, San Francisco, California*. October.
- Matheson, L.J. and P.G. Tratnyek. 1994. *Reductive Dehalogenation of Chlorinated Methanes by Iron Metal*. *Environmental Science and Technology*, 28: 2045-2053.
- Mohn, W. W. and J. M. Tiedje. 1992. *Microbial reductive dehalogenation*. *Microbiological reviews* 56 3: 482-507.
- Naval Facilities Southwest (NAVFAC Southwest). 2001. *Environmental Work Instruction No. 1. Chemical Data Validation*, November 28.
- National Center for Biotechnology Information (NCBI). 2020a. *Compound Summary - 1,1,2-Trichloro-1,2,2-trifluoroethane*. January 30. Available online: <https://pubchem.ncbi.nlm.nih.gov/compound/1%2C1%2C2-trichloro-1%2C2%2C2-trifluoroethane>
- . 2020b. *Compound Summary – Dichlorodifluoromethane*. January 30. Available online: <https://pubchem.ncbi.nlm.nih.gov/compound/Dichlorodifluoromethane>
- . 2020c. *Compound Summary – Trichlorofluoromethane*. January 30. Available online: <https://pubchem.ncbi.nlm.nih.gov/compound/Trichlorofluoromethane>
- NOAA. 2020. *Chlorofluorocarbons (CFCs)*. February. Available online: <https://www.esrl.noaa.gov/gmd/hats/publictn/elkins/cfcs.html>
- Odziemkowski, M.S., T.T. Schuhmaker, R.W. Gillham, and E.J. Reardon (Odziemkowski et al). 1998. *Mechanism of Oxide Film Formation on Iron in Simulating Groundwater Solutions: Raman Spectral Studies*. *Corrosion Studies* 40(2/3): 371-89.
- Oneida Total Integrated Enterprises (OTIE), 2011. *Draft In Situ Anaerobic Bioremediation Treatability Study Completion Report, Remedial Unit C1, Building 253, Hunters Point Naval Shipyard, San Francisco, California*. January 27.
- PRC Environmental Management, Inc. (PRC). 1997. *Parcel C Remedial Investigation Draft Final Report, Hunters Point Shipyard, San Francisco, California*. March.
- . 1994. *Draft Summary Report of Phase I and Phase II UST Removals and Closures in Place, NAVSTA TI, HPA, San Francisco, California*. July 12.
- Rogers, J. David, and S.H. Figuers. 1991. *Engineering Geologic Site Characterization of the Greater Oakland-Alameda Area, Alameda and San Francisco Counties, California*. Rogers/Pacific. December 30.
- San Francisco Redevelopment Agency (SFRA). 2018. *Hunters Point Shipyard Redevelopment Plan Amendment*. July 16.

Shaw Environmental, Inc. (Shaw). 2005. *Final In Situ Sequential Anaerobic-Aerobic Bioremediation Treatability Study, Remedial Unit C5, Building 134, Installation Restoration Site 25, Hunters Point Shipyard, San Francisco, California*. November.

Sonier, D. N., N. L. Duran, and G. B. Smith. 1994. *Dechlorination of trichlorofluoromethane (CFC-11) by sulfate-reducing bacteria from an aquifer contaminated with halogenated aliphatic compounds*. Appl. Environ. Microbiol. 60:4567–4572.

Sullivan, J.B. and R. Krieger. 2001. *Clinical Environmental Health and Toxic Exposures*, Philadelphia: Lippincott Williams & Wilkins, 2001.

SulTech, A Joint Venture of Sullivan Consulting Group, Inc., and Tetra Tech EM Inc (Sultech).. 2008. *Final Feasibility Study Report for Parcel C, Hunters Point Shipyard, San Francisco, California*. July 31.

Tetra Tech EC, Inc. 2017. *Final Remedial Action Completion Report for the Durable Covers Remedy in Parcel C, Hunters Point Naval Shipyard, San Francisco, California*. April.

———. 2010. *Final Basewide Dust Control Plan, Revision 1, Hunters Point Naval Shipyard, San Francisco, California*. November 29.

———. 2003. *Cost and Performance Report, FEROXsm Injection Technology Demonstration, Parcel C, Remedial Unit C4, Hunters Point Shipyard, San Francisco, California*. July 11.

Trevet. 2019. *Final Semiannual Basewide Groundwater Monitoring Report, July 2018 - December 2018, Hunters Point Naval Shipyard, San Francisco, California*. April.

U.S. Coast Survey Office. 1859. *Entrance to San Francisco Bay California. From a Trigonometrical Survey under the direction of A.D. Bache Superintendent of the Survey Of The Coast Of The United States*, available on-line from the David Ramsey Collection: <https://www.davidrumsey.com/maps6080.html>

United States Department of the Navy (Navy). 2010. *Final Record of Decision for Parcel C, Hunters Point Shipyard, San Francisco, California*. September 30.

———. 2005. *Cost and Performance Report Nanoscale Zero-Valent Iron Technologies for Source Remediation*. September.

United States Department of Defense. 2017. *Quality Systems Manual for Environmental Laboratories, Version 5.1 (DoD Environmental Data Quality Workgroup)*.

United States Environmental Protection Agency (EPA). 2020a. *Regional Screening Levels (RSLs) - Generic Tables (TR=1E-06, THQ=0.1)*. February. Available online: <https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables>

———. 2020b. *Risk Management for Trichloroethylene (TCE)*. January 29. Available online: <https://www.epa.gov/assessing-and-managing-chemicals-under-tsca/risk-management-trichloroethylene-tce>

- . 2017a. *National Functional Guidelines for Inorganic Data Review*, EPA-540-R-2017-001.
- . 2017b. *National Functional Guidelines for Organic Data Review*, EPA-540-R-2017-002.
- . 2014. *3PE: A Tool for Estimating Groundwater Flow Vectors*. EPA 600/R-14/273. September.
- . 2004-2014. *SW846 Third Edition, Test Methods for Evaluating Solid Waste, updates IV and V*.
- . 1995-1998. *SW846 Third Edition, Test Methods for Evaluating Solid Waste, updates III/IIIA/IIIB*.
- . 1993-1994. *SW846 Third Edition, Test Methods for Evaluating Solid Waste, updates II/IIA and IIB*.
- . 1992. *SW846 Third Edition, Test Methods for Evaluating Solid Waste, update 1*.

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